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NOISE REDUCTION STUDIES FOR THE U-10 AIRPLANE

By David A. Hilton, Andrew B. Connor, Harvey H. Hubbard and Richard C. Dingeldein

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16. Abstract

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The aural detection distance corresponding to normal cruising flight at an altitude of 1,000 ft over grassy terrain is reduced from 28,000 ft (5.3 miles) to about 50 percent of that value for modification I, and to about 25 percent for modification II. For the aircraft operating at an altitude of 300 ft, the analysis indicates that relatively straightforward modifications could reduce the aural detection distance to approximately 0.9 mile.

Operation of the aircraft at greatly reduced engine speed (1650 rpm) with a 1.3-cu-ft muffler designed by the manufacturer provides aural detection distances slightly lower than modification I.

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SUMMARY

A study was undertaken by the NASA Langley Research Center to determine the noise reduction potential of the U-10 airplane in order to reduce its aural detection distance. Static and flyover noise measurements were made to document the basic airplane noise signature.

Two modifications to the airplane configuration are suggested as having the best potential for substantially reducing aural detection distance with small penalty to airplane performance or stability and control. These modifications include changing the present three-blade propeller to a five-blade propeller, changing the propeller diameter, and changing the propeller gear ratio, along with the use of an engine exhaust muffler.

The aural detection distance corresponding to normal cruising flight at an altitude of 1000 ft over grassy terrain is reduced from 28 000 ft (5.3 miles) to about 50 percent of that value for modification I, and to about 25 percent for modification II. For the aircraft operating at an altitude of 300 ft, the analysis indicates that relatively straightforward modifications could reduce the aural detection distance to approximately 0.9 mile.

Operation of the aircraft at greatly reduced engine speed (1650 rpm) with a 1.3-cu-ft muffler designed by the manufacturer provides aural detection distances slightly lower than modification I.

INTRODUCTION

NASA, in response to a Department of Defense request, has undertaken a study of the noise reduction potential of the U-10 airplane in terms of the aural detection distance. This effort specifically involves: (1) documenting the noise characteristics of the basic airplane in cruising flight, (2) evaluating possible modifications and their associated noise reductions, (3) estimating the effect of some selected modifications on the aural detection distance of the aircraft, and (4) estimating the effects of such noise reduction modifications on the performance and stability of the aircraft. These preliminary studies represent an assessment of the potential overall reductions in noise level rather than a precise design concept that is the optimum from a design viewpoint. This paper documents the NASA efforts in accomplishing the above objectives.

At the suggestion of the manufacturer, noise measurements were also obtained on a potential "quick-fix" configuration consisting of operating the aircraft at very low engine speed and with an experimental muffler installed.

SYMBOLS

A	propeller disk area
$A(x)$	area of blade cross section
B	number of propeller blades
C_D	drag coefficient, $\frac{\text{drag}}{1/2\rho V^2 S}$
C_L	lift coefficient, $\frac{\text{lift}}{1/2\rho V^2 S}$
C_P	power coefficient, $\frac{550\ \text{SHP}}{\rho\ n^3\ D^5}$
C_T	thrust coefficient, $\frac{\text{thrust}}{\rho\ n^2\ D^4}$
D	propeller diameter, ft
J	Bessel function of order mB
M_t	propeller rotational tip Mach number
N	revolutions per minute
Q	propeller shaft torque, lb-ft
R	propeller tip radius, ft
R_e	effective propeller radius, ft
S	wing area

T	thrust
V	velocity, true airspeed
X	slant range distance from airplane to observer
dB	decibels, re 0.0002 $dynes/cm^2$
f	frequency, cps
m	order of harmonic of propeller
n	revolutions per second
p	root-mean-square sound pressure of given harmonic, lb/ft^2
q_o	free-stream dynamic pressure
q_t	dynamic pressure at the tail
s	distance from propeller to observer, ft
x	percent propeller radius
ψ	azimuth angle measured from the thrust axis of propeller (0^o is in front)
η	propeller efficiency, $\frac{C_T}{C_P} \cdot \frac{V}{nD}$
σ	propeller blade element solidity
ρ	mass density of air
ω	propeller angular velocity, rad/sec
cps	cycles per second
V/nD	propeller advance ratio parameter
M.A.C.	mean aerodynamic chord
MRP	military rated power
NRP	normal rated power
R/C	rate of climb
SHP	shaft horsepower

SPL	sound pressure level
TAS	true airspeed
THP	thrust horsepower
T.O.	take-off

Subscripts

e	engine
p	propeller
max	maximum

APPARATUS AND METHODS

Test Airplane

The U-10 airplane is a five-place cantilever-high-wing monoplane of approximately 3000 pounds gross weight. It is powered by a 295-hp horizontally opposed six-cylinder engine which drives a three-blade, constant-speed, 8.0-ft-diameter tractor propeller at a 77:120 reduction ratio. Photographs of the test airplane are shown in figure 1, and a three-view diagram with a list of the principal physical dimensions is presented in figure 2. Both static and flyby noise measurements were originally made with a military version of the airplane having a standard exhaust system and provided by the Air Section, Continental Army Command, Ft. Monroe, Virginia.

Additional noise measurements were obtained with an essentially similar civil version of the airplane, both with and without installation of an experimental muffler designed and fabricated by the Helio Aircraft Corporation (see fig. 1(a)). This latter airplane and a test pilot for these tests were provided by the manufacturer.

The noise signatures obtained for each aircraft at selected operating conditions (no muffler on civil version) exhibited similar characteristics. However, since more extensive measurements were made for the civil version, it is primarily these data that will be presented and discussed in this paper. The conclusions are considered applicable to the military aircraft.

Test Conditions

Noise measurement tests were conducted on the military airplane October 12, 1966, and the civil airplane February 9, 1967, at the NASA Wallops Station, where use was made of the main paved runway surface and the associated flat terrain for locating instrumentation and for obtaining both static and flyby noise measurements.

Typical terrain features of the Wallops test area are shown in the photographs of figure 3(a), which is a view looking north from the runway center line, and figure 3(b) which is a view to the south. A schematic diagram of the microphone arrays for these tests is illustrated in figure 4.

Noise Measuring Equipment

The noise measuring instrumentation for these tests is illustrated by the block diagram of figure 5. The microphones were of a conventional piezoelectric ceramic type having a frequency response flat to within ±3 dB over the frequency range of 20 to 12 000 cps. The outputs of all the microphones at each station were recorded on multichannel tape recorders. The entire sound measurement system was calibrated in the field before and after the flight measurements by means of conventional discrete frequency calibrators supplied by the microphone manufacturers. The data records were played back from the tape (using the playback system shown in figure 5) to obtain the sound pressure level time histories and both broad-band and narrow-band spectra.

Aircraft Operation

Static noise surveys.- Tests of the normally configured civil airplane and the muffler-equipped civil airplane were conducted at three engine speeds: 1650, 2400, and 2750 rpm, as listed in table I. The data were taken with the microphones positioned in the static arrays as shown schematically by figure 4(a) at 30° intervals on a 50-ft radius from the propeller hub.

Flyover noise surveys.- In the flyover noise tests the aircraft were flown over a ground track, as shown schematically in figure 4(b). The aircraft were operated at 1650, 2400, and 2750 engine rpm at altitudes ranging from 300 to 1500 ft and at velocities ranging from 62 to 133 mph (see table I). Precise geometric altitude and course direction information were measured and recorded using a GSN/5 radar tracking unit. Position information was provided as an assist to the pilot to maintain proper course and altitude. The desired flight path was maintained for about 1 mile prior to and beyond the overhead position.

Atmospheric Conditions

Observations of local surface temperature, humidity, wind velocity, and direction were made during the times of these tests. The temperature on February 9, 1967, at the Wallops Island test site ranged from about

-3° C at the surface to about -7° C at 2000 ft over the 6-hour test period. The relative humidity was approximately 75 percent and winds were out of the north from 0 to 5 knots over this same period.

MEASURED NOISE CHARACTERISTICS OF THE BASIC AIRPLANE

The analytical study to define the noise-reduction potential for the U-10 aircraft, and which will be summarized later in the paper, is based on operating the engine at 2750 rpm, which is representative of current practice. Data were obtained for engine speeds other than 2750 rpm even though they are not in general use.

Static Noise Signature

A sample narrow-band analysis of the noise recorded in the plane of the propeller at a distance of 50-ft for the standard airplane is presented in figure 6 for 2750 rpm (static run no. 1 of table I). These data were obtained with the aid of a 3 cps bandwidth filter and are depicted for the range of frequencies up to about 500 cps. Shown in the figure are the individual noise components corresponding to the significant engine firing frequencies and the propeller noise frequencies. The engine frequencies are indicated as some integral multiple times the cylinder firing frequency f, which for a four-cycle engine is equal to the revolutions per second divided by 2. The propeller noise components are identified by their mB values, where m is the harmonic number and B is the number of blades. Results of similar narrow-band analyses of the noise components represented by figure 6 are listed in table II for several other azimuth stations.

Flyover Noise Signatures

Measurements on basic aircraft.- The flyover noise signatures of the two versions of the standard configuration of the U-10 airplane are presented in figure 7 for 2750 engine rpm. The maximum value in each octave band is plotted in the figure regardless of the time during the flyover at which it occurred. It can be seen that the overall values are nearly equal and the variations with the octave-band center frequencies are roughly similar, although unexplained differences exist in some of the higher frequency octave bands.

The effect of operating the basic civil aircraft at engine speeds of 2750, 2400, and 1650 rpm is shown in figure 8. Corresponding airspeeds are 133, 124, and 62 mph, respectively (see table I). Compared to the 2750 rpm case, the peak noise level at 2400 rpm increases slightly but remains in the third octave band (125 cps center frequency). The decreased noise levels indicated at the higher frequencies would not be expected to affect the aural detection distance. At 1650 rpm, the reduced engine and propeller speed is seen to have shifted the maximum noise to the second octave band (63 cps center frequency).

Measurements with manufacturer's muffler.- An experimental muffler was designed by the Helio Aircraft Corporation and made available for these flight tests. This muffler, which is shown installed on the aircraft in figure 1(a), has a volume of 1.3 cu ft. With the muffler installed, engine operation is limited to about 80 percent of rated power due to the limited exhaust area provided. Results obtained from aircraft flyovers at an altitude of 300 ft with the muffler installed are presented in figure 9 for 2750, 2400, and 1650 rpm. Inasmuch as the engine exhaust is a major contribution to the overall noise of this aircraft (see fig. 6, for example), exhaust muffling should be effective in quieting the aircraft. This is shown by the data plotted in figure 9. The combined effects of the exhaust muffler and the decreased propeller noise contribution by virtue of the reduced tip Mach number have dropped the corresponding overall sound pressure levels by an average of 13 dB. The overall sound pressure levels with the muffler installed are indicated in figure 9 to be relatively insensitive to the engine speed.

AIRCRAFT MODIFICATIONS ANALYZED FOR THIS STUDY

Using the measured noise spectrum obtained for the basic U-10 aircraft with normal engine operation at 2750 rpm, studies were made using available analytical techniques to reduce the aircraft noise by means of propeller changes and engine exhaust mufflers. These studies were conducted with the view of obtaining significant noise reductions in the critical octave bands with minimum effect on aircraft performance. Hence, the propeller efficiency in various flight conditions, including its static-thrust capability, was an important factor, as was the ability of the muffler to quiet the engine without limiting its ability to deliver rated power. The modifications selected as indicative of practical fixes that can provide substantial reductions in the aural detection distance of this aircraft are listed in table III, in which two modifications are briefly described. Details of the propeller and the muffler analyses are given in appendixes A and B, respectively. The effect on overall aircraft weight is presented in appendix C, and the estimated performance of the U-10 aircraft equipped with modification I or modification II is estimated and compared with the basic U-10 in appendix D.

The simplest modification (modification I) involves changing the number of propeller blades from three to five, reducing the propeller diameter from 8.0 to 7.0 ft to reduce the tip Mach number without the need for a gearing change, and the addition of a 2-cu-ft muffler. The estimated overall noise reduction for this modification from a 300-ft reference altitude is about 11 dB. A further noise reduction of about 7 dB would be obtained by means of the changes of modification II. This latter modification requires, in addition to the 2-cu-ft muffler designed for modification I, changing the propeller engine gear ratio from 77:120 to 44:120 and increasing the propeller diameter to 9.0 ft. For the two modifications, the estimated net weight increases range from 17 to 100 lb, respectively.

ESTIMATED NOISE CHARACTERISTICS OF THE MODIFIED AIRPLANE

The estimated maximum flyover octave band spectra for a 300-ft reference altitude for the preceding two proposed aircraft modifications are presented in figure 10, along with a comparison of the measured and estimated spectra for the standard U-10 airplane. Estimated values of the latter noise spectrum are seen to be in fairly close agreement with the measured ones.

DETERMINATION OF AURAL DETECTION DISTANCE FOR BASIC AND MODIFIED AIRCRAFT

Basic Assumptions Relating to Detection

In addition to the noise source characteristics (see refs. 1 and 2) it is well known that the aural detection of a noise involves such factors as the transmission characteristics of the path over which the noise travels (see refs. 3, 4, 5, 6, and 7) and the acoustic conditions at the observer location (see refs. 4 and 8) as well as the hearing ability of the observer (see ref. 9). Attempts have been made to account for all of the pertinent factors in the above categories for the calculations of detection distance which follow.

Attenuation factors.- The attenuation factors associated with the transmission of noise from the source to the observer are assumed to involve the well-known inverse distance law, atmospheric absorption due to viscosity and heat conduction, small-scale turbulence, and terrain absorption which is weighted to account for the elevation angle between the source and the observer. For the purposes of this paper these factors are taken into account as determined by the following equation:

$$\text{P.L. } (f,x) = 20 \log_{10} \frac{x}{A} + \left[K_1 + K_2 + \left(K_3 - K_1\right) K_4\right] \frac{x}{1000}$$

where propagation loss (P.L.) is computed for each frequency and distance combination and where the first term on the right-hand side of the equation accounts for the spherical spreading of the waves. In this connection x is the distance for which the calculation is being made and A is the reference distance for which measured data are available. The remaining terms which represent propagation losses and which are given in coefficient form are defined as follows:

K_1 represents the atmospheric absorption due to viscosity and heat conduction and is expressed in dB per 1000 ft. The values of K_1 vary as a function of frequency and for the purposes of this paper are those of the following table. For frequencies up to 500 cps data are taken from reference 3 and for the higher frequencies from reference 6.

Octave band no.	Center frequency	dB loss per 1000 ft
1	31.5	-
2	63	0.1
3	125	.2
4	250	.4
5	500	.7
6	1000	1.4
7	2000	3.5
8	4000	7
9	8000	14.5

K_2 is the attenuation in the atmosphere due to small-scale turbulence. A value of 1.3 dB per 1000 ft is assumed independent of frequency for the frequency range above 250 cycles (see ref. 7).

K_3 also is expressed in dB per 1000 ft and includes both atmospheric absorption and terrain absorption. The values used are those of reference 4 which are listed for widely varying conditions of vegetation and ground cover. The data of reference 4 have been reproduced in a more convenient form in reference 5. Calculations included herein make use of the data of reference 5 particularly curve (b) of figure 1, which represents the condition of thick grass cover (18 inches high) and the upperbound of curve 3 of figure 2, which represents conditions of leafy jungle with approximately 100 ft "see through" visibility. K_4 is a weighting factor to account for the angle, measured from the ground plane, between the noise source and the observer. The values of K_4 assumed for the present calculations were taken from figure 3 of reference 5 and are seen to vary from zero for angles greater than 7° to 1.0 for an angle of 0°.

<u>Ambient noise level conditions and human hearing</u>.- The detectability of a noise is also a function of the ambient masking noise conditions at

the listening station and the hearing abilities of the listener. Since they are somewhat related, they will be discussed together.

The ambient noise level conditions assumed for these studies were based on data from references 4 and 8 which were obtained in jungle environments. It was indicated in reference 3 that a noise made up of discrete tone components is detectable if it is within 9 dB of the background noise (random in nature) in any particular octave band. Thus, the corresponding measured spectra of references 4 and 8 have been reduced by 9 dB to account for the above difference in the masked and the masking spectra. The only exception to this procedure was employed in the evaluation of modification II. For this case the critical noise component for detection was the broad-band vortex noise. At frequency bands where vortex noise was critical the background noise levels referred to above were <u>not</u> reduced by 9 dB.

The resulting octave band spectra have been further adjusted to account for critical band width of the human ear (ref. 9), according to the following equation, to give masking level values for each band.

$$\text{Masking level, dB} = \text{octave band level, dB} - 10 \log_{10} \left[\frac{\Delta f_{octave}}{\Delta f_{critical}} \right]$$

where the Δf_{octave} and $\Delta f_{critical}$ values corresponding to standard octave band center frequencies are given in the following table:

Octave band center freq., cps	31.5	63	125	250	500	1000	2000	4000	8000
Δf_{octave}, cps	22	44	88	177	354	707	1414	2828	5656
$\Delta f_{critical}$, cps	--	--	50	50	50	66	100	220	500
$10 \log_{10} \frac{\Delta f_{octave}}{\Delta f_{critical}}$	--	--	2.5	5.5	8.5	10.7	11.5	11.1	10.5

The values of the last row in the above table have been subtracted from the octave band values to adjust them to the masking level spectra which define the boundaries of the jungle noise criteria detection region of figure 11.

Likewise a threshold of hearing curve for the unaided ear (taken from ref. 3) is made use of since it represents the levels of pure tone noise that are just detectable on the average by healthy young adults. The implication here is that noises having levels lower than those of the threshold of hearing curve at corresponding frequencies will not be detectable. Thus the threshold of hearing curve is the determining factor of detection at the lower frequencies.

No attempt is made to account for possible binaural effects in the studies of the present paper.

Estimation Methods

Reference detection distances for each aircraft configuration for flight altitudes of 1000 and 300 ft and for ground cover conditions representative of both 18-in. grass and 100-ft see-through leafy jungle, have been determined with the aid of figure 11 and the basic noise signature data of figure 10. In figure 11 the octave band noise levels at various distances have been estimated by taking into account the appropriate atmospheric and terrain losses. Also shown in the figure is a threshold of hearing curve and a band labeled "jungle noise detection criteria." The lower boundary of this area represents masking levels in a relatively quiet jungle location in the Canal Zone (ref. 4). The upper boundary, on the other hand, represents a relatively more noisy masking level condition based on measurements in Thailand (ref. 8). These data have been compared with and found to be generally compatible with results of recent, but unpublished, jungle noise surveys taken at Fort Clayton in the Canal Zone. In the determination of the maximum distance at which the aircraft can be detected aurally, it was assumed that such detection was possible at distances at which the level of aircraft noise in any octave band equaled or exceeded either the masking level curve or the threshold of hearing curve, whichever was more appropriate.

The results of the distance estimates are summarized in table IV for each aircraft configuration depicted in figure 10 and for the two altitude and ground cover conditions. Also included in the table for comparison are the detection distances estimated for the U-10 aircraft operating at greatly reduced engine speed (1650 rpm), with and without the manufacturer's 1.3-cu-ft muffler installed, based on the corresponding measured noise signatures shown in figures 8 and 9. The values listed in table IV are presented in descending order of maximum detection distance obtainable for various configurations. Also indicated in the table are effects of altitude and terrain conditions.

EFFECTS OF AIRCRAFT OPERATION AND GROUND OBSERVER CONDITION

Table IV indicates clearly how the location of the listener relative to the noise source plays an important part in detection distance estimates. Reducing the altitude of operation of the basic airplane from 1000 ft to 300 ft reduces the detection distance by almost 50 percent. Also, if the listener is located in a leafy jungle position, the detection distance is reduced over the corresponding detection distance for open grassy terrain. These effects are illustrated in detail for the standard airplane in figure 11.

EFFECTS OF AIRPLANE CONFIGURATION MODIFICATIONS

Modification I involves no change in the gearing but does include a 2-cu-ft muffler, an increase in the number of propeller blades from three to five, and a decrease in propeller diameter from 76 in. to 64 in. It is indicated in table IV that this modification will result in reductions of the aural detection distances from 28 000 to 14 000 ft and from 14 800 to 8800 ft for altitudes of 1000 and 300 ft, respectively, over grassy terrain. For flight at an altitude of 300 ft over dense jungle, the aural detection distance would be reduced from 9400 ft to 6300 ft by modification I.

More extensive changes are involved in modification II, which includes use of the same 2-cu-ft muffler and involves changing the propeller engine gear ratio of 44:120. In addition, a 9-ft diameter five-blade propeller is used. The detection distances for this modification are estimated to be 7500 and 4900 ft for 1000 and 300 ft altitudes, respectively, over grassy terrain. These distances become 7300 and 4500 ft, respectively, for flights over dense jungle.

The estimated noise spectra at various distances are presented in figure 11(e) through 11(h) for all configurations studied for a 300-ft altitude over grassy ground cover. Note that the detection distance criterion was modified as previously described and as illustrated in figure 11(e) for modification II because of the broad-band character of its noise in the critical octave band for detection.

The major effect on aircraft weight, performance, and stability and control estimated for the two suggested modifications is summarized as follows:

Effects of configuration changes	Modification no.	
	I	II
Net increase in airplane weight, lb	17	100
Increase T.O. distance over a 50-ft obstacle (basic airplane 520 ft), ft	33	29
Decrease in sea level R/C (basic airplane 1460 ft/min), ft/min	52	29
Decrease in V_{max}, knots	0	1
Increase in V_{stall}, knots	0	0

Appendix D also contains a statement that the airplane static margin increases from modification I to modification II as more weight is added at the nose of the airplane. Low-speed control sensitivity will probably decrease slightly when the slipstream dynamic pressure decreases as a result of the larger diameter propeller.

Substantial reductions in the aural detection distance of the basic aircraft equipped with the manufacturer's experimental 1.3-cu-ft muffler and operated at 1650 rpm are also provided, the results indicating a slight advantage over the proposed modification I. Operating the basic aircraft (no muffler) at 1650 rpm is seen to have substantially no effect on the aural detection distance.

CONCLUDING REMARKS

A study has been undertaken to determine modifications to the U-10 airplane which would be useful in reducing its aural detection distance in cruise flight.

Analysis of the basic airplane noise signatures indicates that the main noise sources are the propeller and reciprocating-engine exhaust and, hence, modifications to reduce the noise of the airplane will require modifications to both the propeller and engine exhaust system.

Estimated aural detection distance reduction to about 50 percent of the 28 000 ft determined for the basic airplane is achievable by means of modification I which involves changing the number of propeller blades from two to five, reducing the diameter from 8 ft to 7 ft, and adding a 2-cu-ft expansion-chamber-type muffler. The net weight increase for this configuration is 17 lbs and there is no change in V_{max} and V_{stall}.

The reduction of aural detection distance to approximately 25 percent of that for the basic airplane can be achieved with modification II which involves a five-blade 9-ft-diameter propeller, a change in the propeller gear reduction ratio to 44:120, and the inclusion of a 2-cu-ft expansion chamber muffler. The net weight increase for this configuration is 100 lbs and there are minor performance penalties in take-off distance, rate of climb, and V_{max}.

For the aircraft operating at an altitude of 300 ft, the analysis indicates that the relatively straight forward modifications considered herein could reduce the aural detection distance to approximately 0.9 mile.

Operation of the aircraft at greatly reduced engine speed (1650 rpm) with a 1.3-cu-ft muffler designed by the manufacturer provides aural detection distances slightly lower than modification I.

REFERENCES

1. Hubbard, Harvey H.; and Maglieri, Domenic J.: An Investigation of Some Phenomena Relating to Aural Detection of Airplanes. NACA TN 4337, September 1958.

2. Vogeley, A. W.: Sound-Level Measurements of a Light Airplane Modified to Reduce Noise Reaching the Ground. NACA Rep. 926, 1949 (Supercedes NACA TN 1647).

3. Loewy, Robert G.: Aural Detection of Helicopters in Tactical Situations. Journal of the American Helicopter Society, vol. 8, no. 4, October 1963.

4. Eyring, Carl F.: Jungle Acoustics. The Journal of the Acoustical Society of America, vol. 18, no. 2, October 1946.

5. Gayne, William J.: Aural Detection of an Aerial Vehicle Operating at Low Altitudes. AIAA paper no. 65-329, July 1965.

6. Anon.: ARP 866, Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise. Society of Automotive Engineers, August 1964.

7. Regier, Arthur A.: Effect of Distance on Airplane Noise. NACA TN 1353, 1947.

8. Anon.: Acoustic and Seismic Research. Semi-Annual Report No. 3 (ASTIA No. AD 473784) Jansky and Bailey, Research and Engineering Division of Atlantic Research Corporation, October 1965.

9. Fletcher, Harvey: Auditory Patterns. Reviews of Modern Physics, vol. 12, January 1940.

Table I.- Summary of aircraft operating conditions for both the static and flyover noise measurements.

Item No.	Run No.	Altitude above ground, ft.	Lateral disp. from track ℄ ft.	Velocity MPH	Engine speed, RPM	Manifold pressure, in. Hg	Engine brake horsepower	Flap setting, degrees
STATIC								
1	1	—	—	—	2750	20	166	—
	2	—	—	—	2400	20	138	—
	3	—	—	—	1650	29.5	145*	—
FLIGHT								
1	1	300	0	133	2750	20	166	0
	2	300	0	124	2400	20	138	0
	3	300	0	62	1650	23.5	108*	15
2	1	1000	0	130	2750	20	166	0
	2	1000	0	120	2400	20	138	0
	3	1000	0	62	1650	22.5	102*	15
3	1	1500	0	133	2750	20	166	0

* denotes flight condition requiring engine settings outside range specified in the flight manual for this aircraft.

Table II.- Narrow band data from the standard configuration airplane for 2,750 engine rpm, distance from propeller hub to microphones is 50 feet.

Frequency cps	Harmonics: Cylinder, f	Harmonics: Prop., mB	Sound levels, dB at ψ = 360°	330°	300°	270°	240°	210°
23	1		84	87	85			
46	2							
69	3		83	84	85			
88		3	94	96	98	108	108	99
92	4		91	88	86	96	96	93
115	5		77	79	76	81	83	84
138	6		102	100	99	108	105	107
161	7		74	72	75			
176		6	86	88	91	102	95	90
184	8		77	80	84	84	83	87
207	9		83	84	85	91	86	92
230	10		80	82	81	82	87	94
253	11		78	75	75	83		81
264		9	89	89	87	94	91	91
277	12		94	91	91	97	85	90
300	13		80	81	80	84		83
323	14		86	79	80	88	83	88
346	15		83		78	87	84	90
353		12	86	90	87	92	91	84
369	16		89	87	80	92	85	83
392	17		83	80	80	88	85	84
415	18		86	80	78	80	85	89
438	19			75	72	78	82	80
441		15	88	89	85	88	89	84
461	20		76	74				
484	21		72	77	73	82	85	79
501	22		74	75	76	78	86	79

Table III.- Summary of the aircraft modifications suggested by this study listing the principal changes in aircraft geometry, weight, and overall noise levels.

Aircraft Configuration	Propeller *			Muffler **	Net Aircraft Weight Increase lbs.	Estimated Overall Noise Level (distance 300 ft.)
	prop rpm / engine rpm	Dia. ft.	No. of Blades	Volume cu. ft.		
Basic U-10	77/120	8	3	----	-----	96 dB (measured) 96 dB (calculated)
Modification I	77/120	7	5	2	17	84 dB
Modification II	44/120	9	5	2	200	77 dB

* Controllable-pitch propeller
** External muffler (belly location)

Table IV.- Tabulation of the minimum aural detection distances estimated for each configuration analyzed in this study. The table shows the effects of both altitude and terrain cover.

Aircraft Altitude ft.	Ground Cover	Reference Detection Distance, ft. Aircraft Configuration: Basic Measurement	Basic Calculation	1650 Case w/o muffler	Mod. I	1650 Case w/muffler	Mod. II
1000	Grassy	28,100 (b)	27,200 (b)	41,000 (a)	14,400 (b)	13,200 ([illegible])	[illegible],700 (bac)
1000	Leafy	17,000 (b)	1[illegible],600 (b)	16,200 (a)	11,200 (b)	10,600 (b)	[illegible],700 (bac)
300	Grassy	21,500 (b)	15,200 (b)	44,000 (a)	8,900 (b)	12,000 (a)	5,800 (c)
300	Leafy	9,600 (b)	9,400 (b)	7,100 (a)	6,400 (b)	6,100 (aab)	4,700 (c)

(a) Data from 2nd octave band.

(b) Data from 3rd octave band.

(c) Data from 5th octave band.

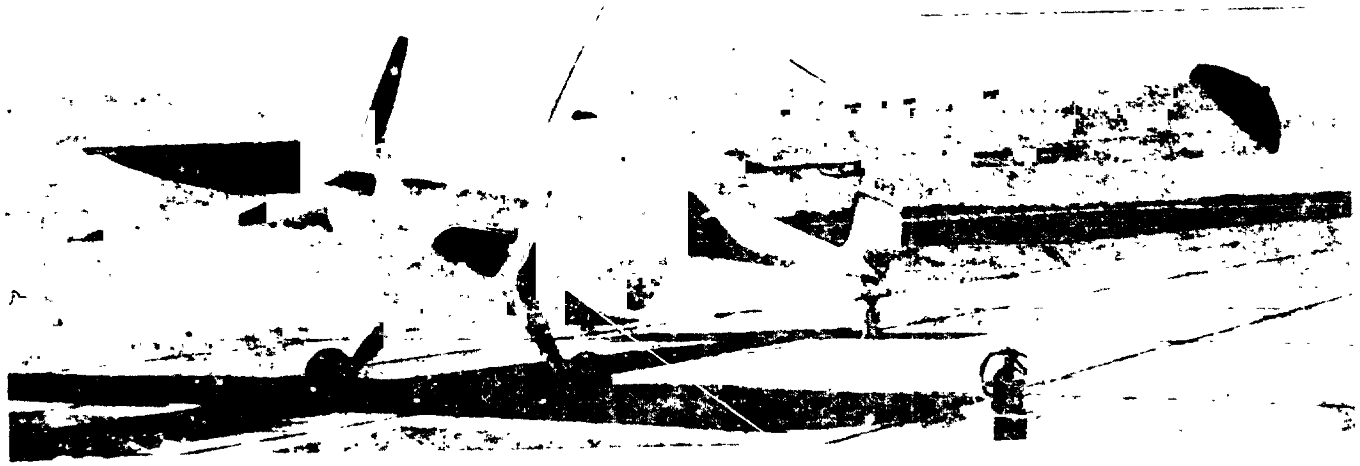
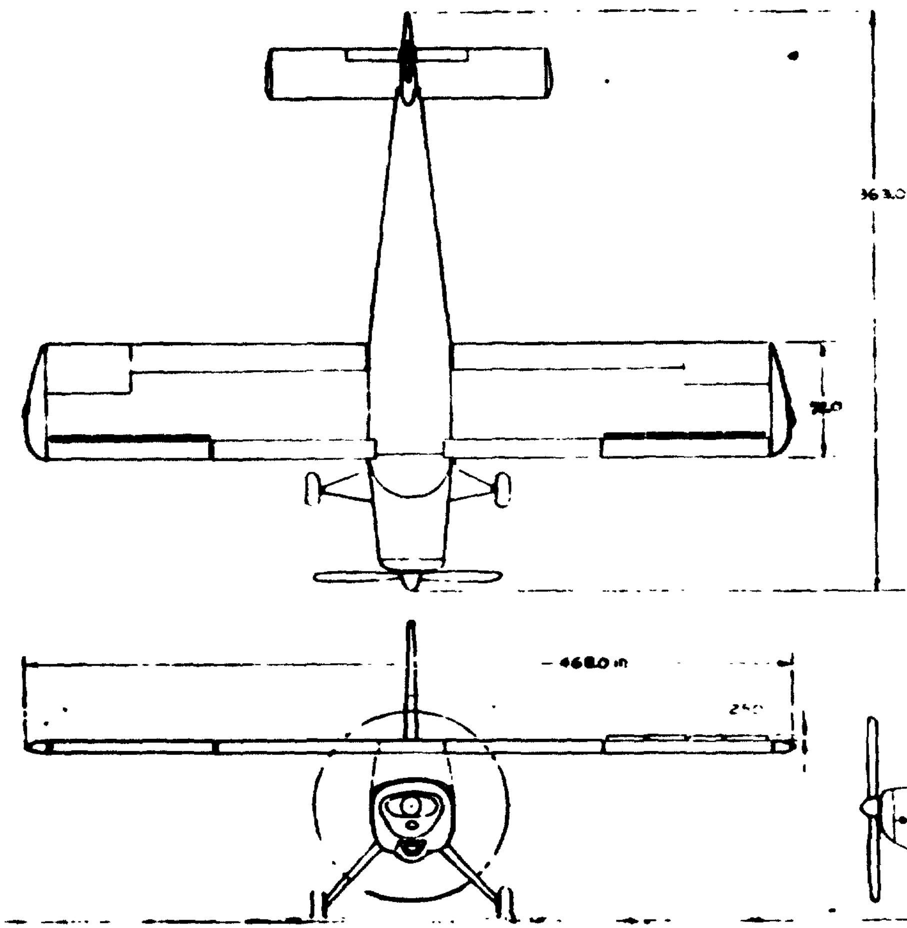


Figure 1 (a)-Front quarter view of the military test airplane

Figure 1 (b)-Rear quarter view of the military test airplane.



Weights	
Gross weight	3000 lbs.
Empty weight	Approx. 2300 lbs.
Power Plant	
Lycoming GO-480-G1D6	
Take-off HP at 3400 rpm	295
Rated HP at 3000 rpm	260
Propeller - Hartzell 96 in. 3 blade constant speed	
Wing	
Area (slats retracted)	231 sq. ft.
Aspect Ratio	6.58
Airfoil Section	NACA 23012
Taper Ratio	1.0
Twist (geometric)	0°
Mean Aerodynamic Chord	71.47 in.
Span	468 in.
Dihedral	+1°
Incidence, Root Chord	+3°
Horizontal Tail (Stabilator)	
Wing Area Ratio	16%
Span	180 in.
Airfoil Section	NACA 0012
Taper Ratio	1.00
Chord	30 in.
Aspect Ratio	6.0
Vertical Tail	
Area (including fin)	25.80 sq. ft.
Height	58.90 in.
Root Chord Airfoil Section	NACA 0015
Tip Chord	NACA 0009
Aspect Ratio	2.33
Rudder Area/Total Area	41%
Fin Area/Total Area	59%

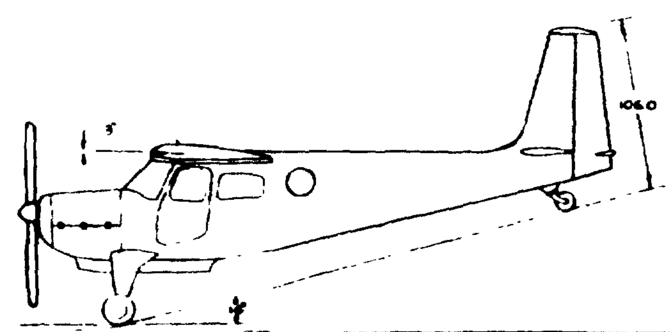


Figure 2.-Three view sketches of the U-10 airplane with a listing of its principal physical features.

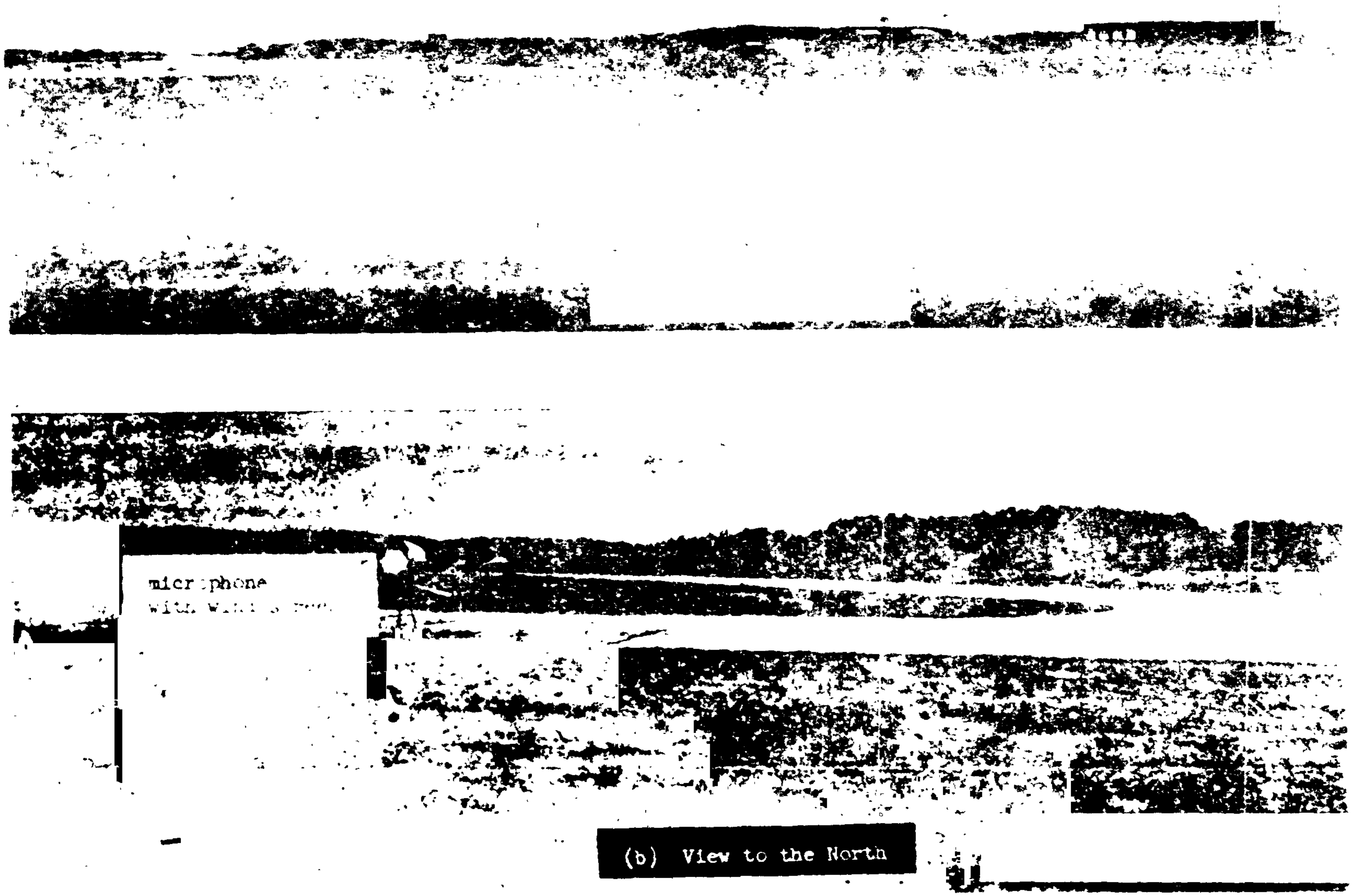
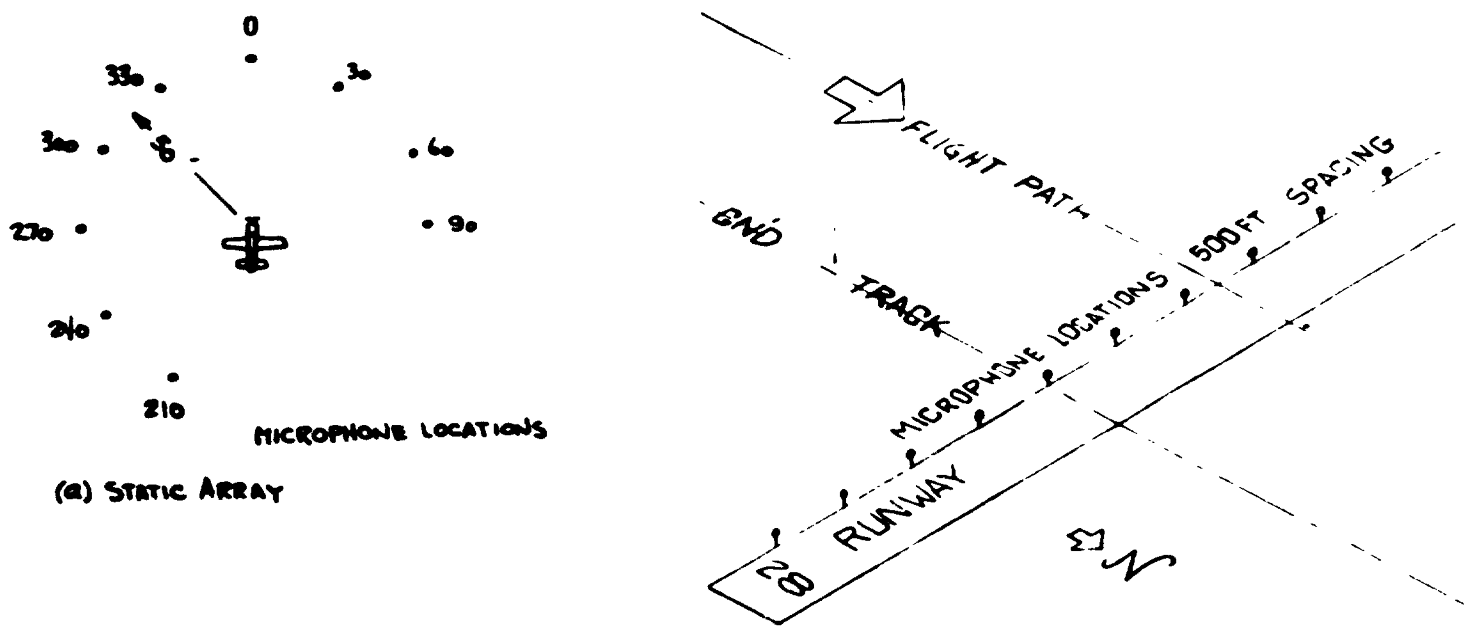


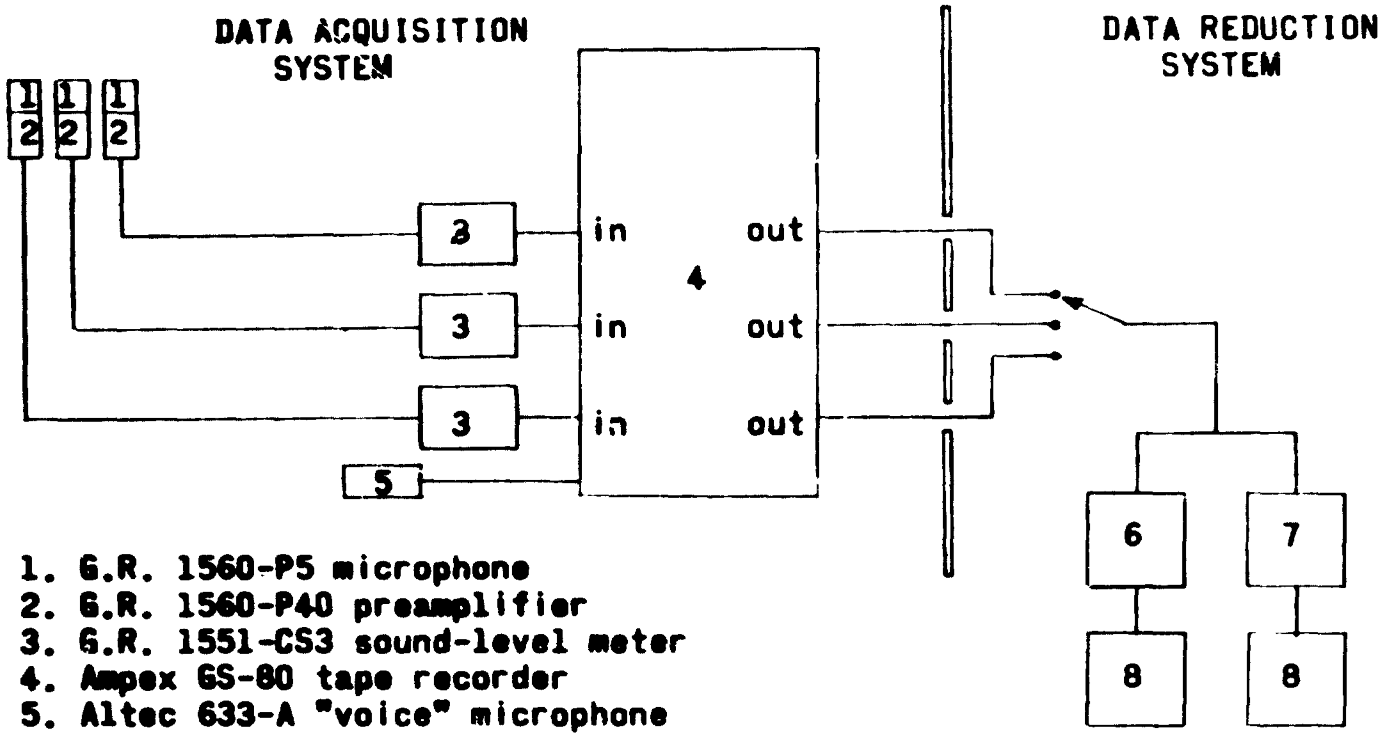
Figure 3.- Photographs of the NASA Wallops Island test area showing the runway and flat terrain.



(a) STATIC ARRAY

(b) FLYBY ARRAY

Figure 4.- Diagram of the microphone arrays illustrating the aircraft location for noise measurement during both static and flyby operations.



1. G.R. 1560-P5 microphone
2. G.R. 1560-P40 preamplifier
3. G.R. 1551-CS3 sound-level meter
4. Ampex GS-80 tape recorder
5. Altec 633-A "voice" microphone
6. G.R. 1558-AP octave-band analyzer
7. G.R. 1900-A wave analyzer
8. G.R. 1521-B graphic level recorder

Figure 5.- Block diagram showing system lay ut for noise data acquisitic n and reducti n.

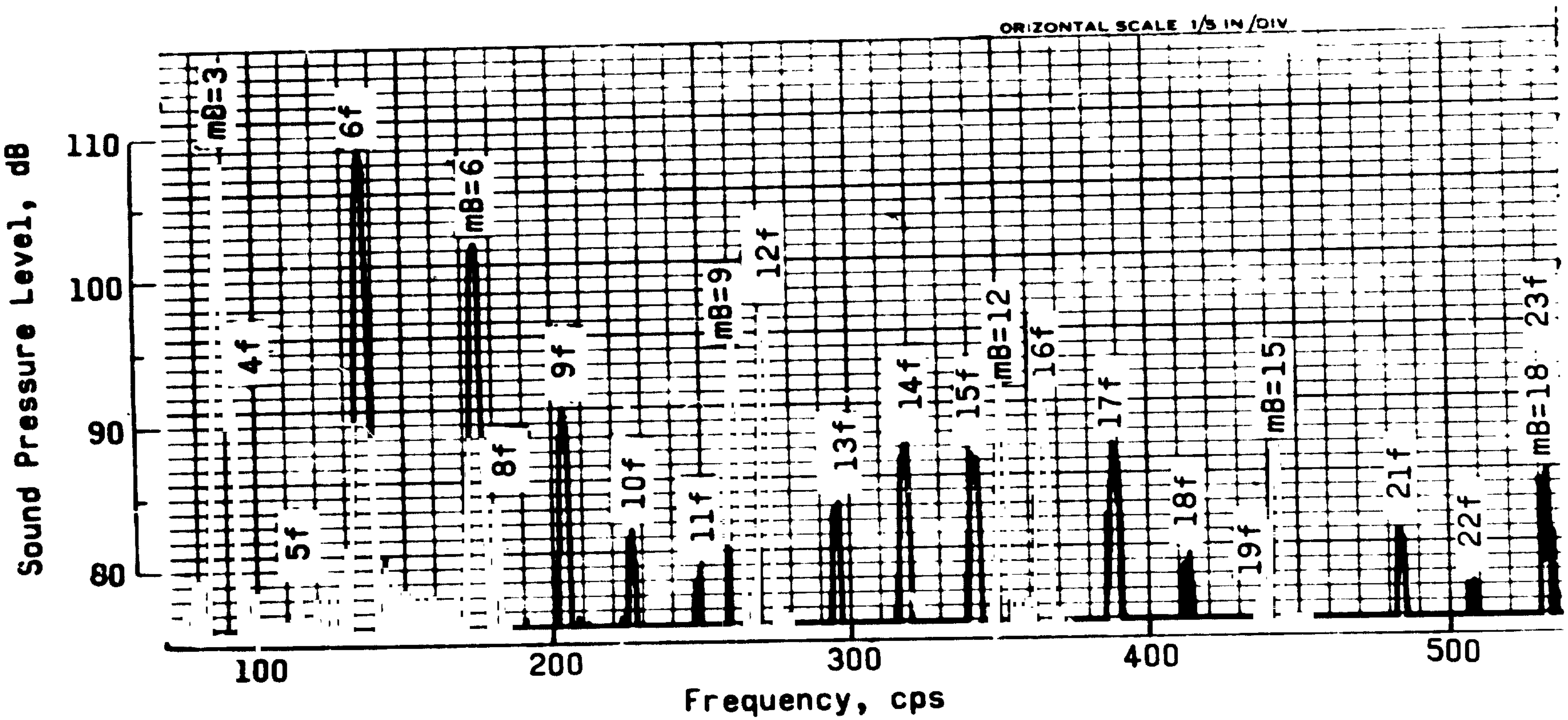


Figure 6.- Typical narrow band record of the propeller and engine noise from the test airplane. N_E = 2,750 rpm, ψ = 270°, r = 50 ft.

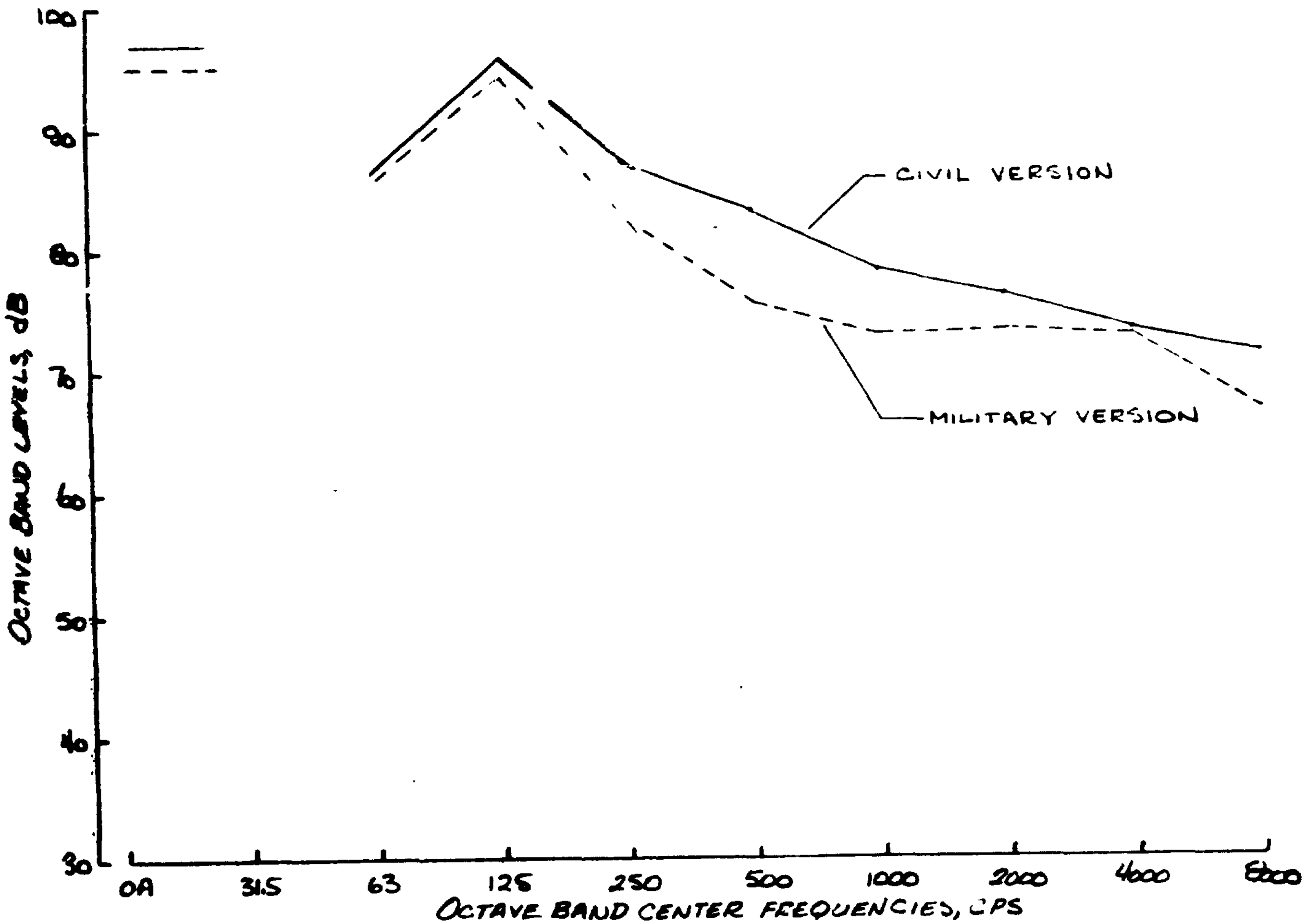


Figure 7.- Flyover octave band spectra of the standard configurations of the civil and military versions of the U-10 airplane. Altitude = 300 ft., N_E = 2,750 rpm

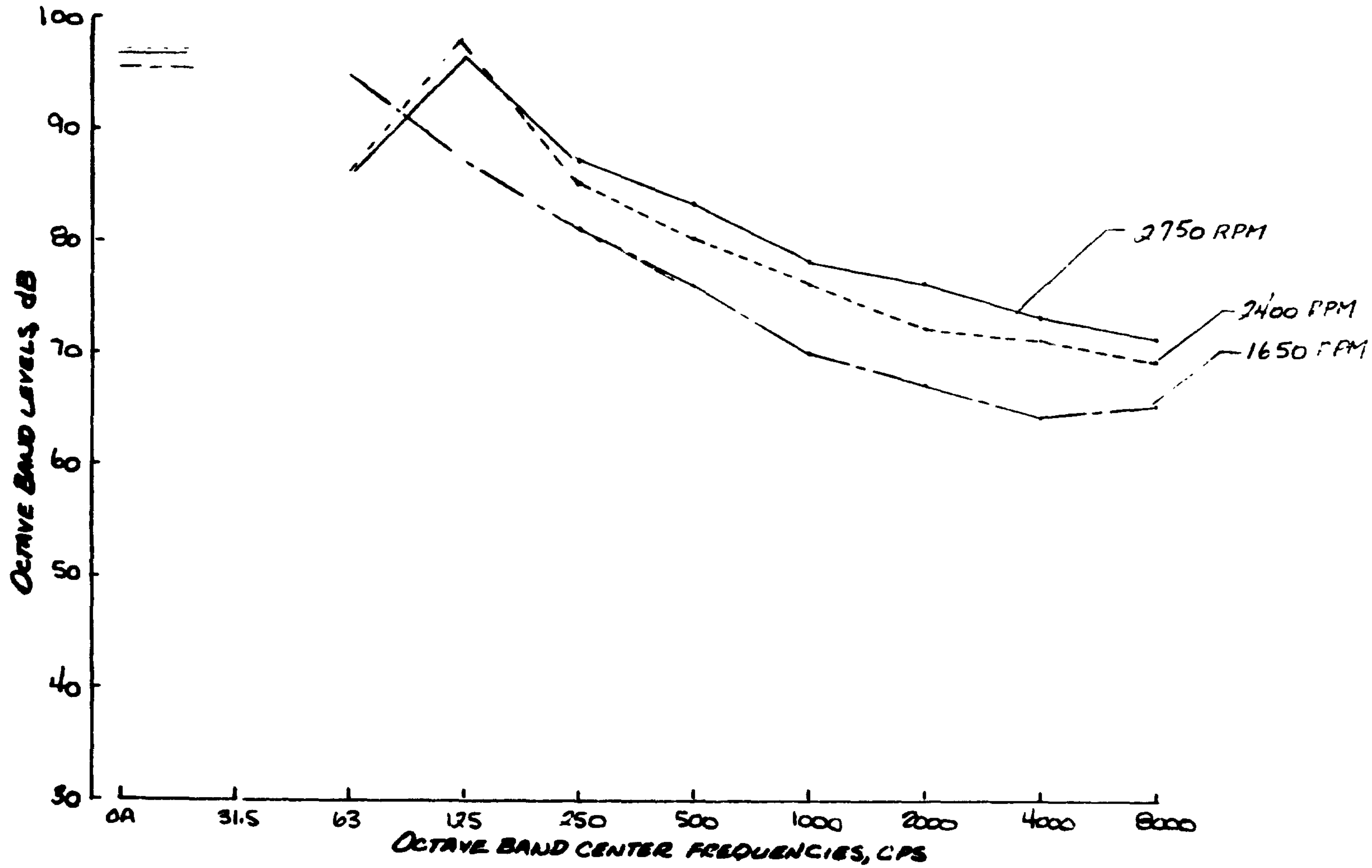


Figure 8.- Flyover octave band spectra for the standard civil version of the U-10 aircraft. Altitude = 300 ft.

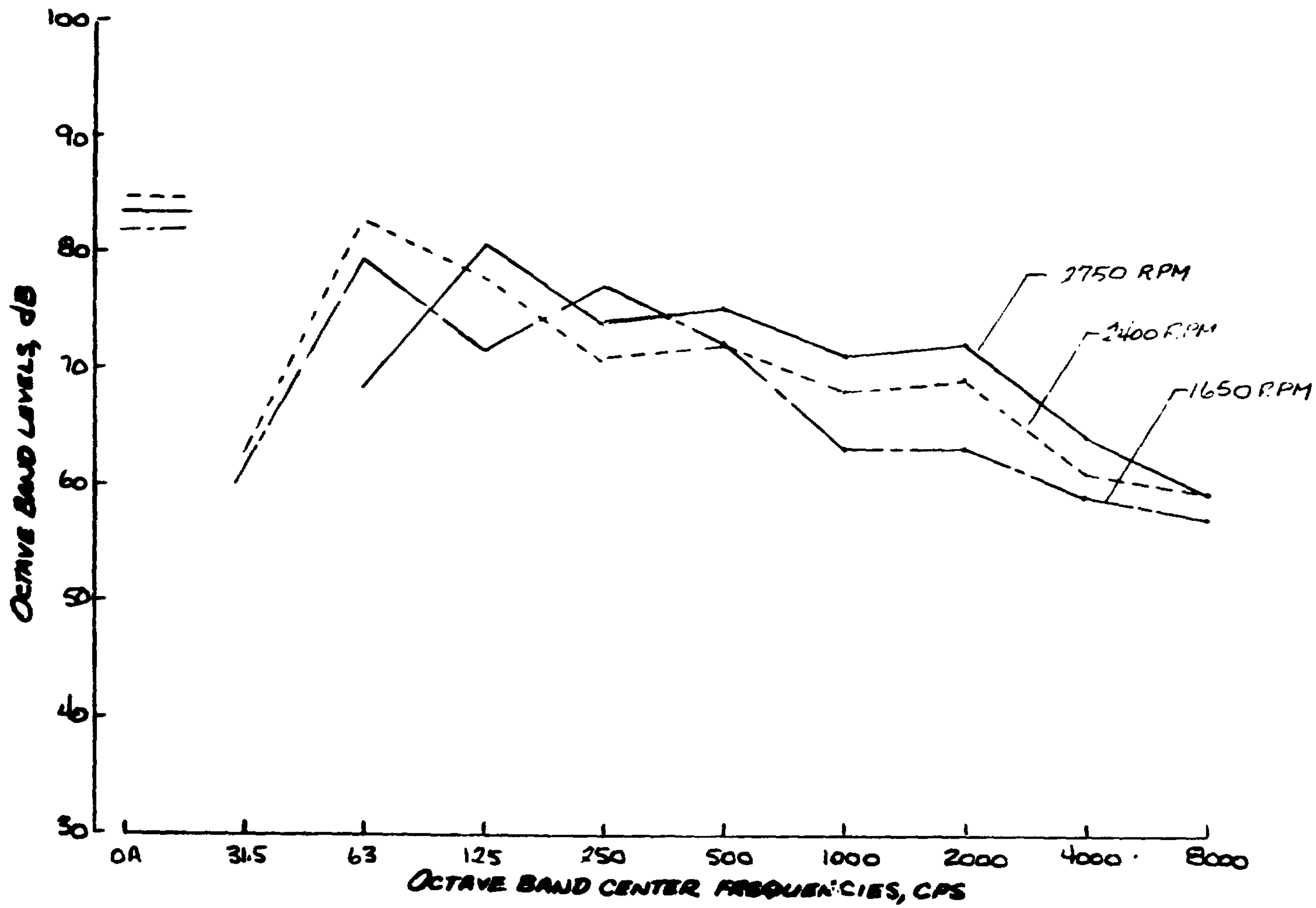


Figure 9.- Flyover octave band spectra for the civil version of the U-10 aircraft equipped with the manufacturer's 1.3 cu. ft. muffler. Altitude = 300 ft.

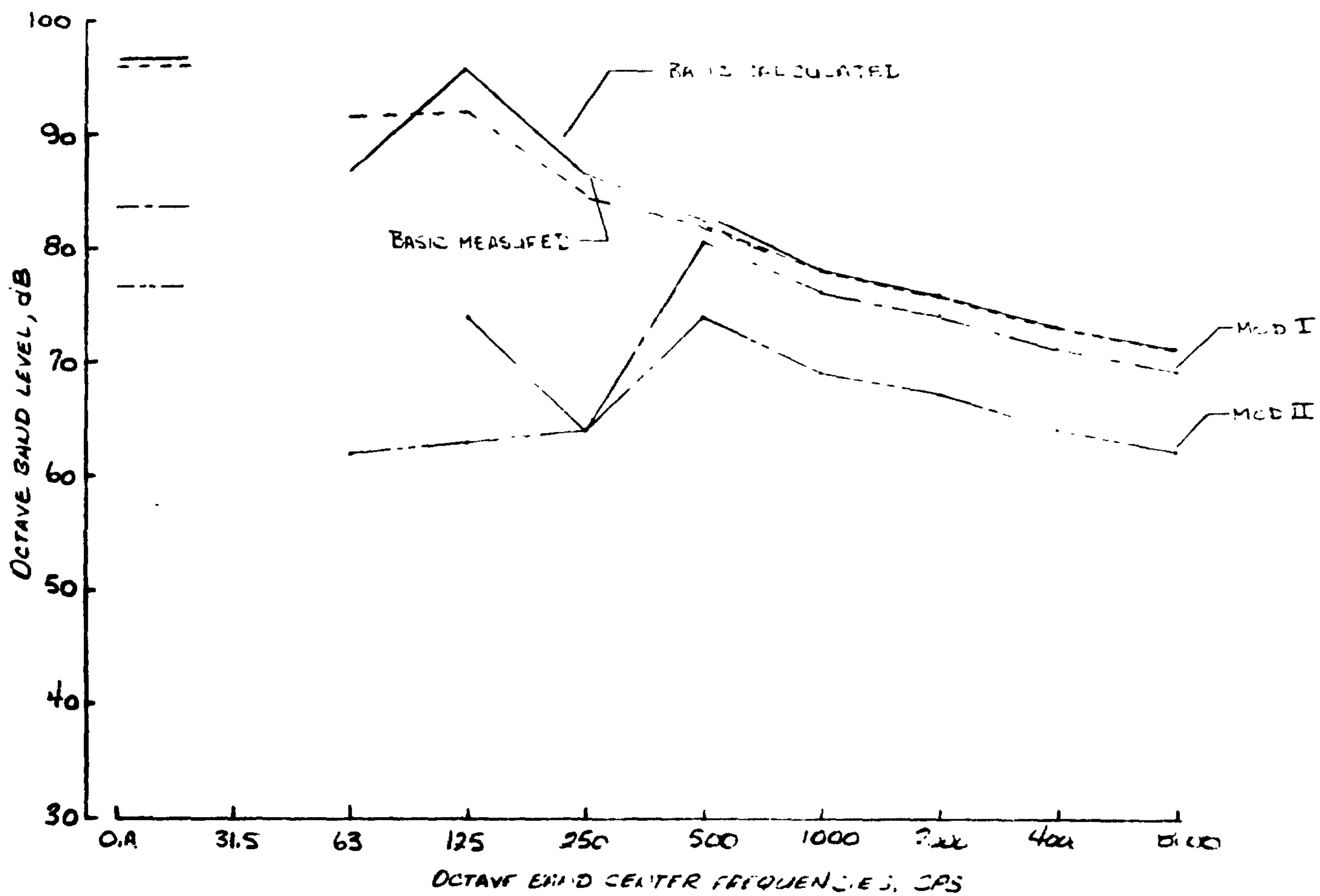


Figure 10 - Octave band spectra of the U-10 airplane for each of the proposed modifications, and a comparison of the estimated spectrum with the measured spectrum of the standard airplane. N_E = 2,750 rpm, altitude = 300 ft.

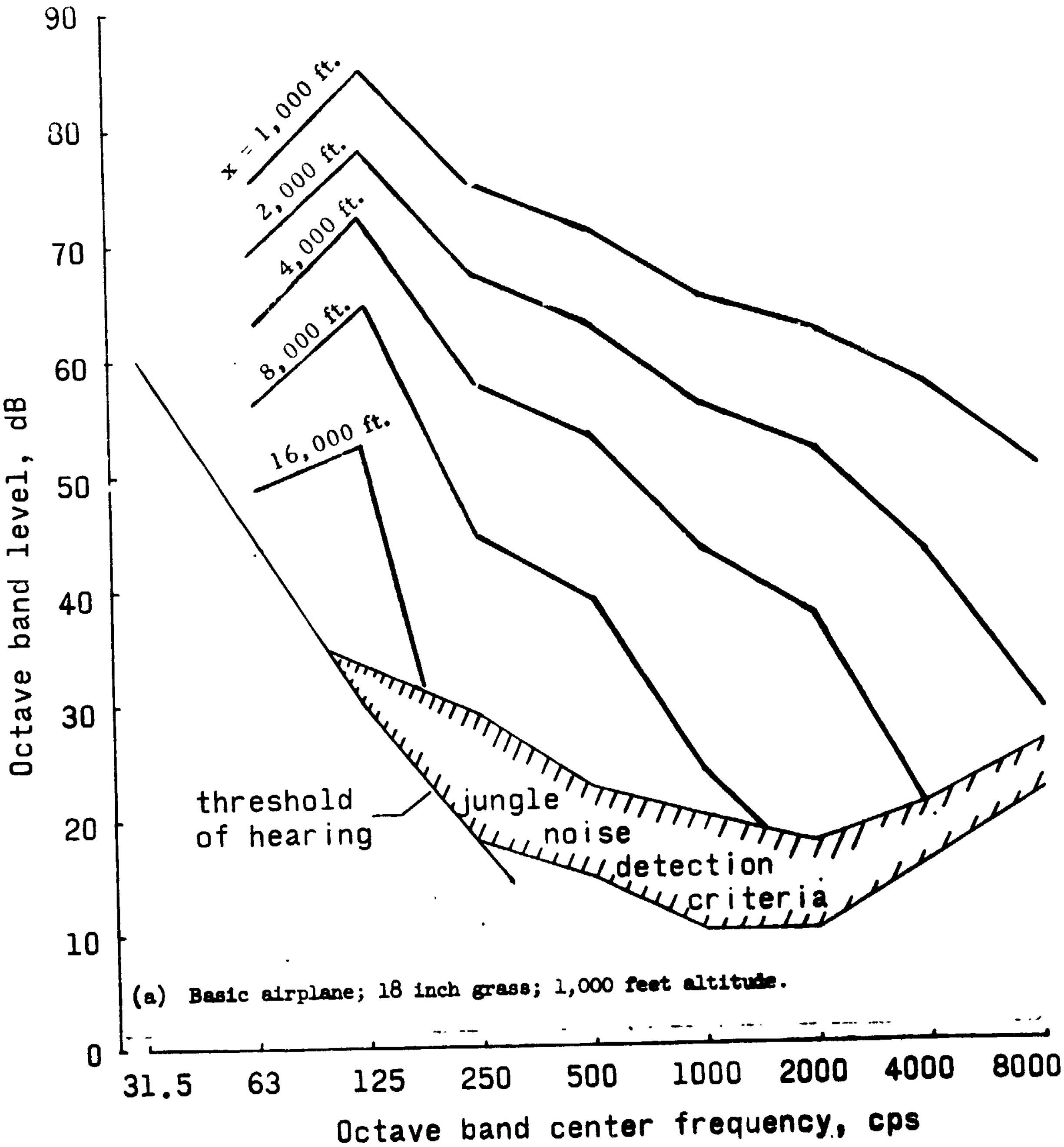


Figure 11.- Effect of slant range and types of terrain on the U-10 noise signature.

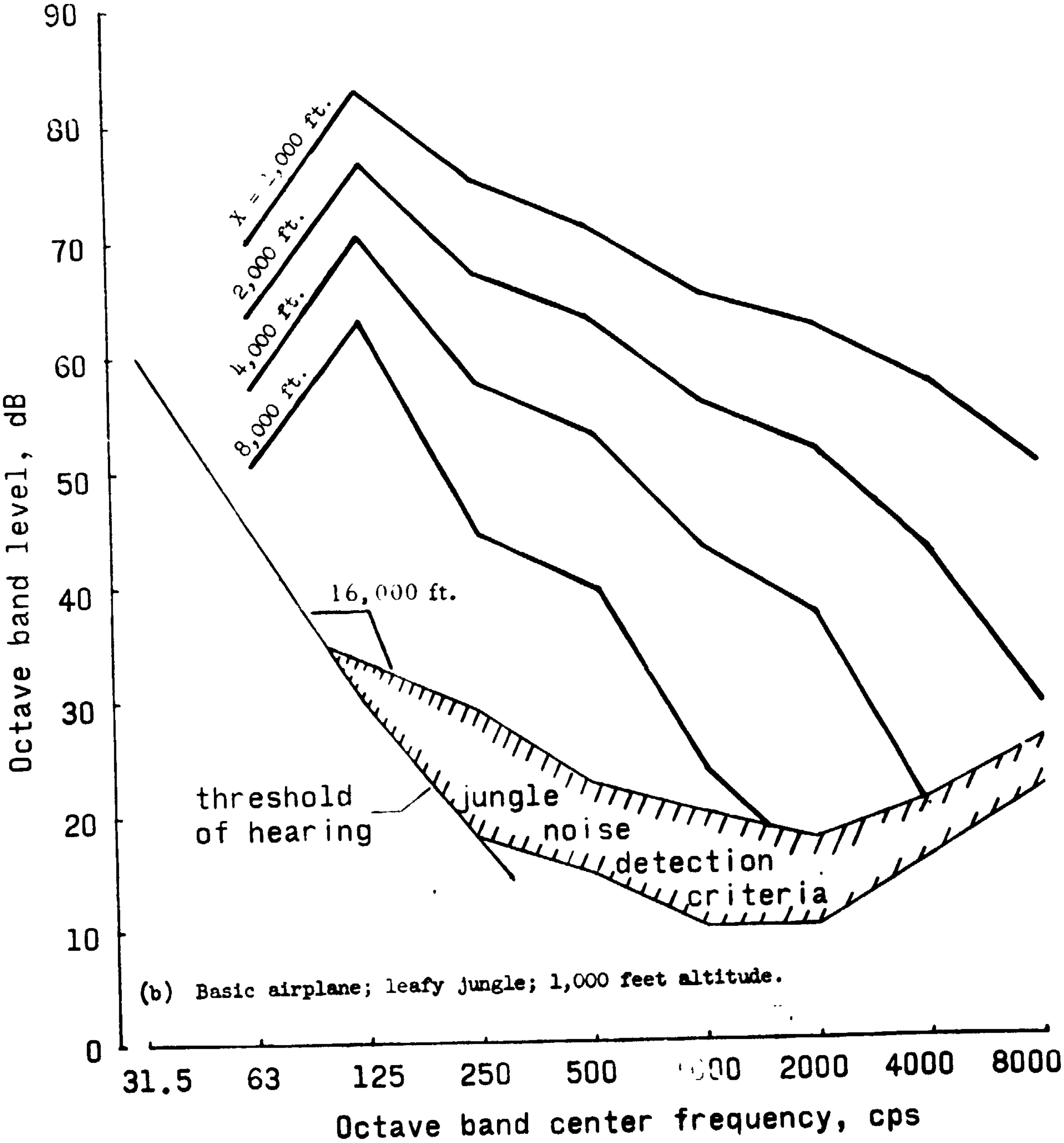


Figure 11.- Continued

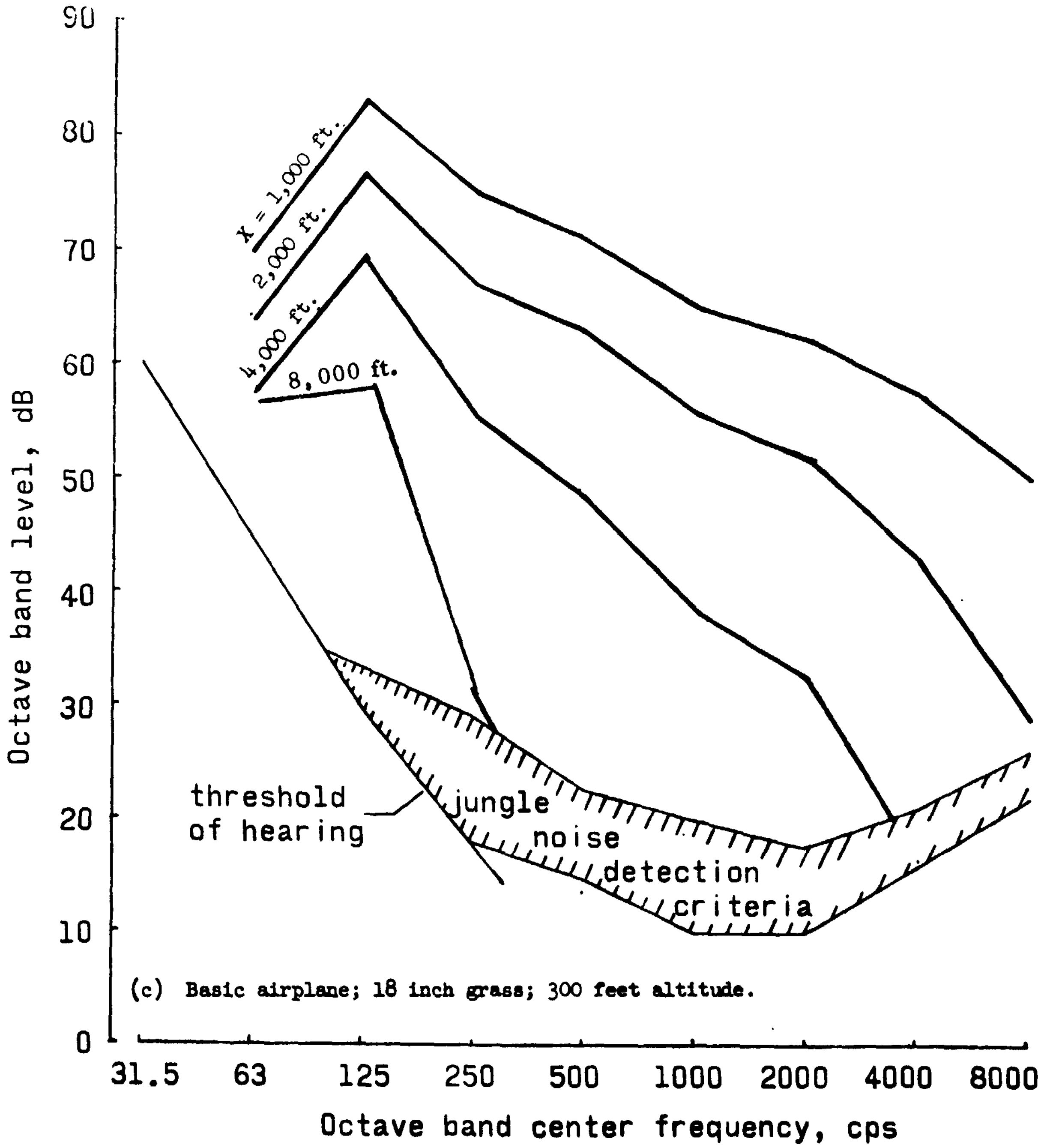


Figure 11.- Continued

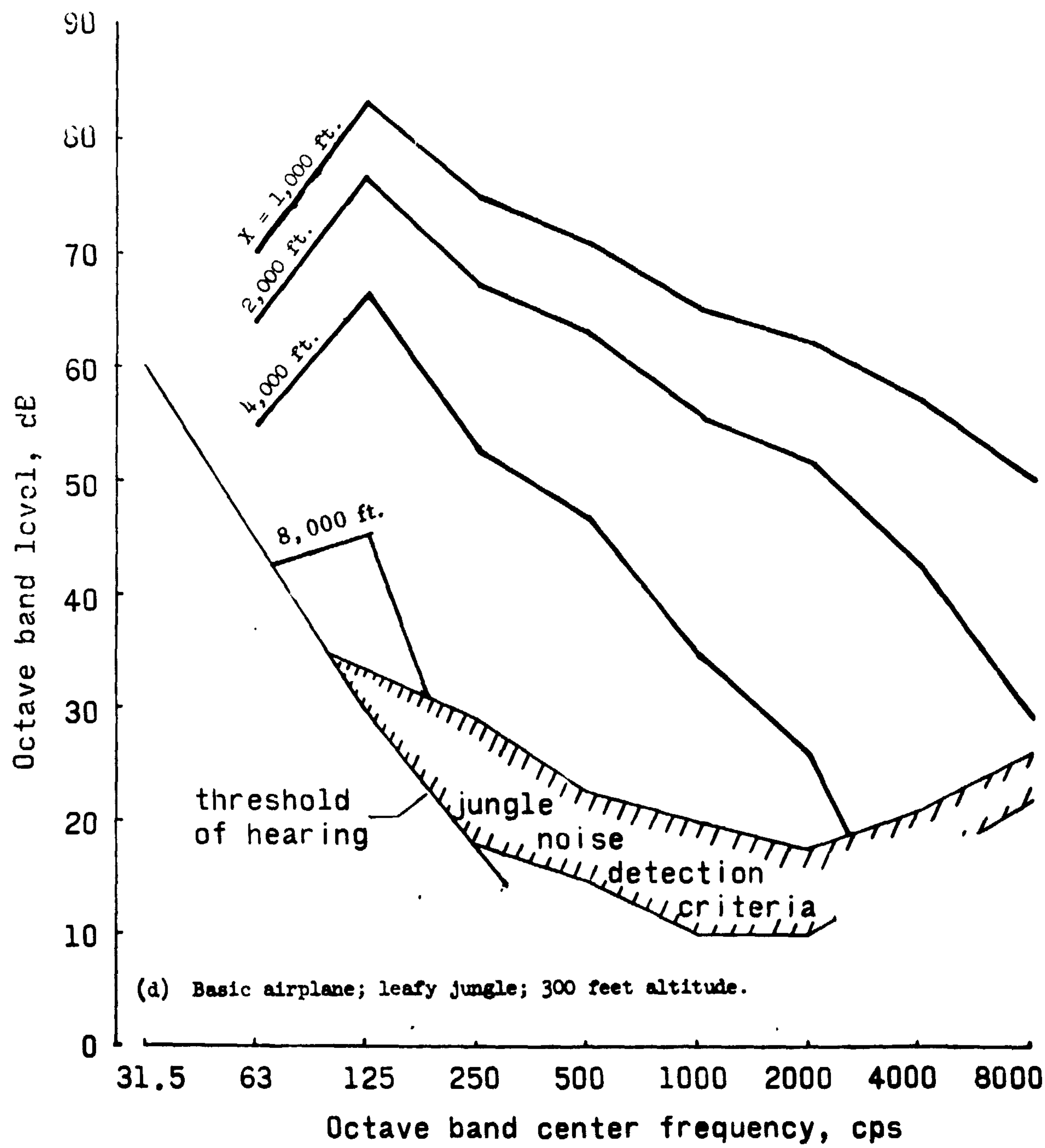
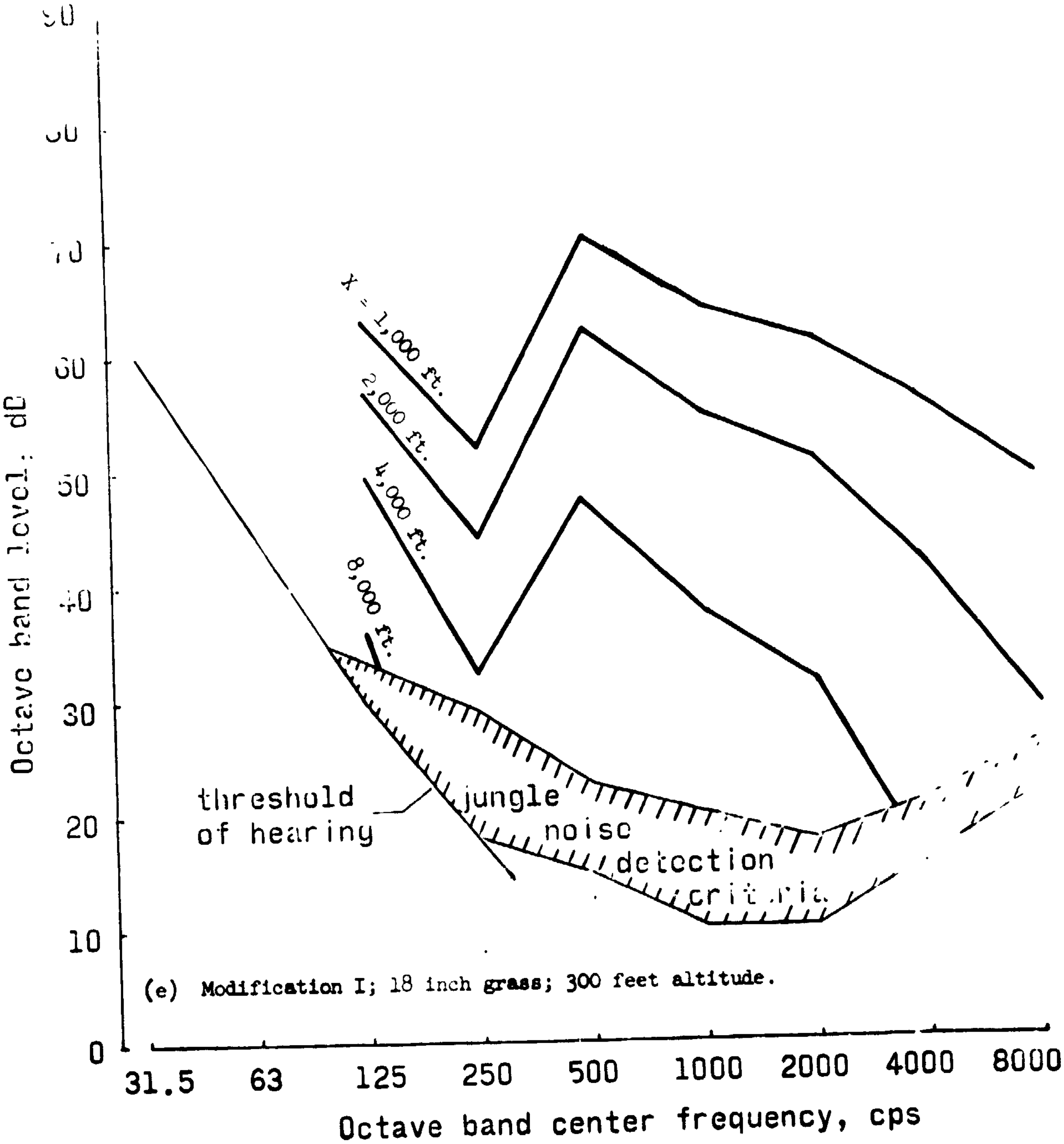


Figure 11.- Continued



(e) Modification I; 18 inch grass; 300 feet altitude.

Figure 11.- Continued

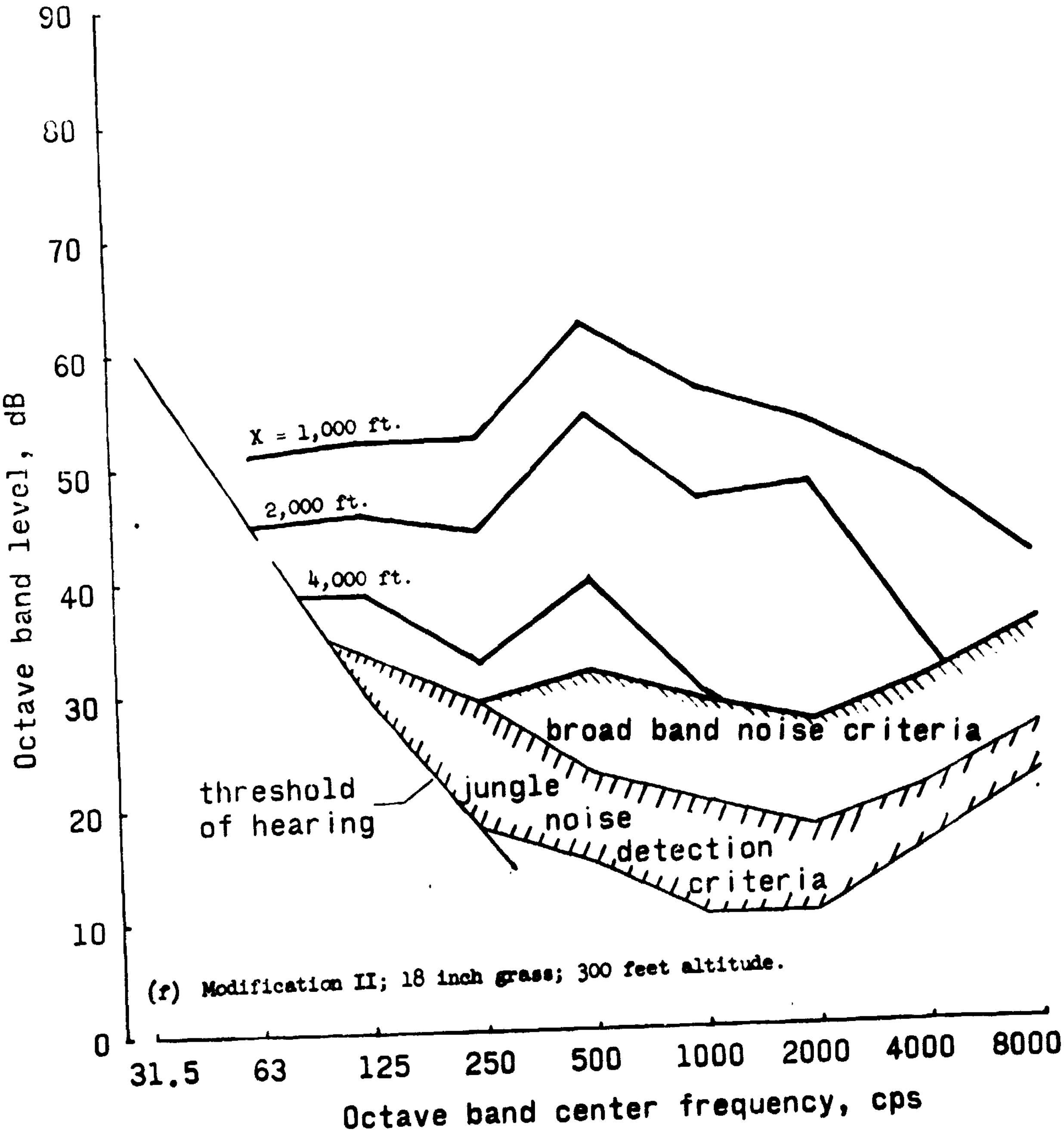
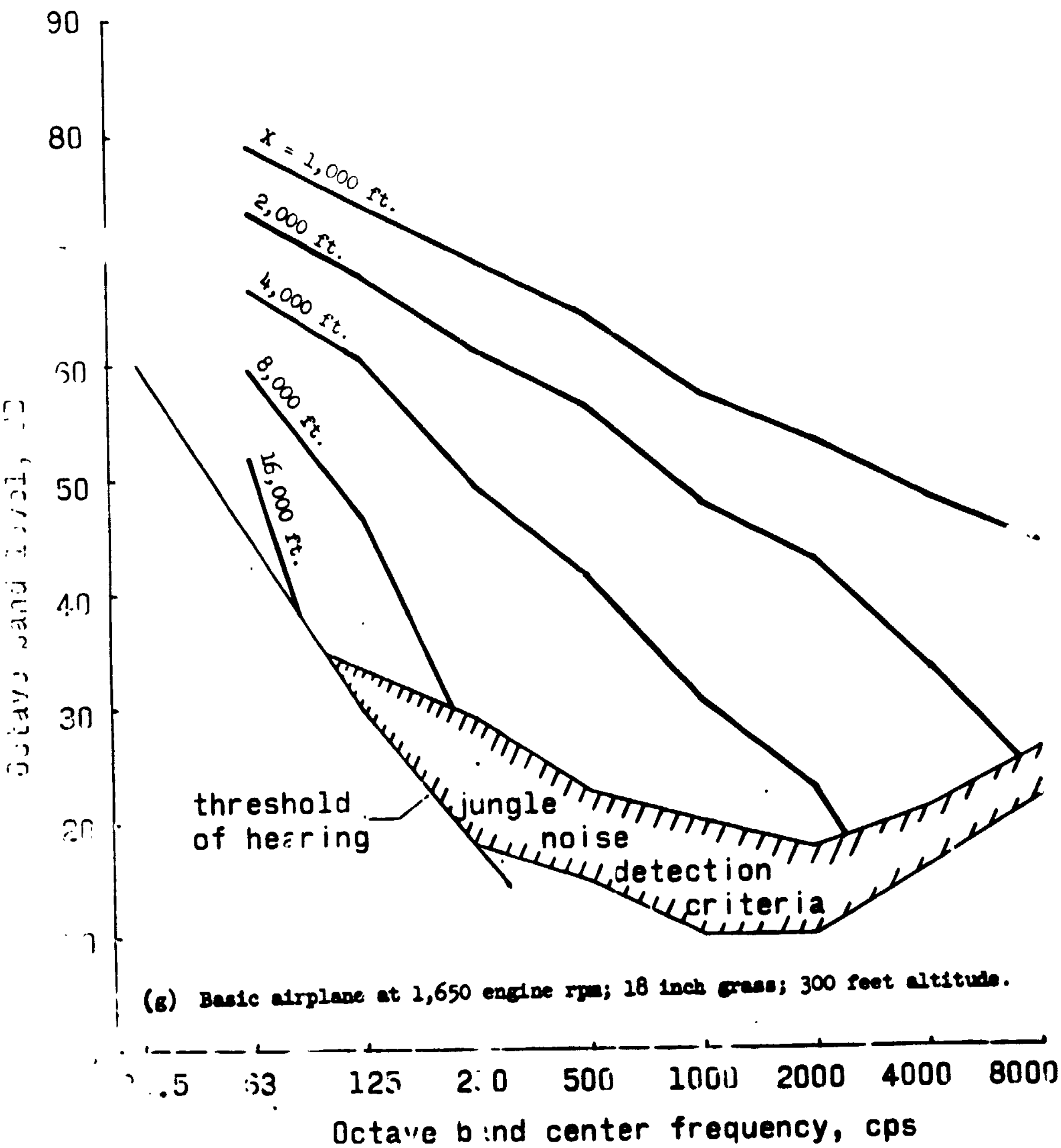
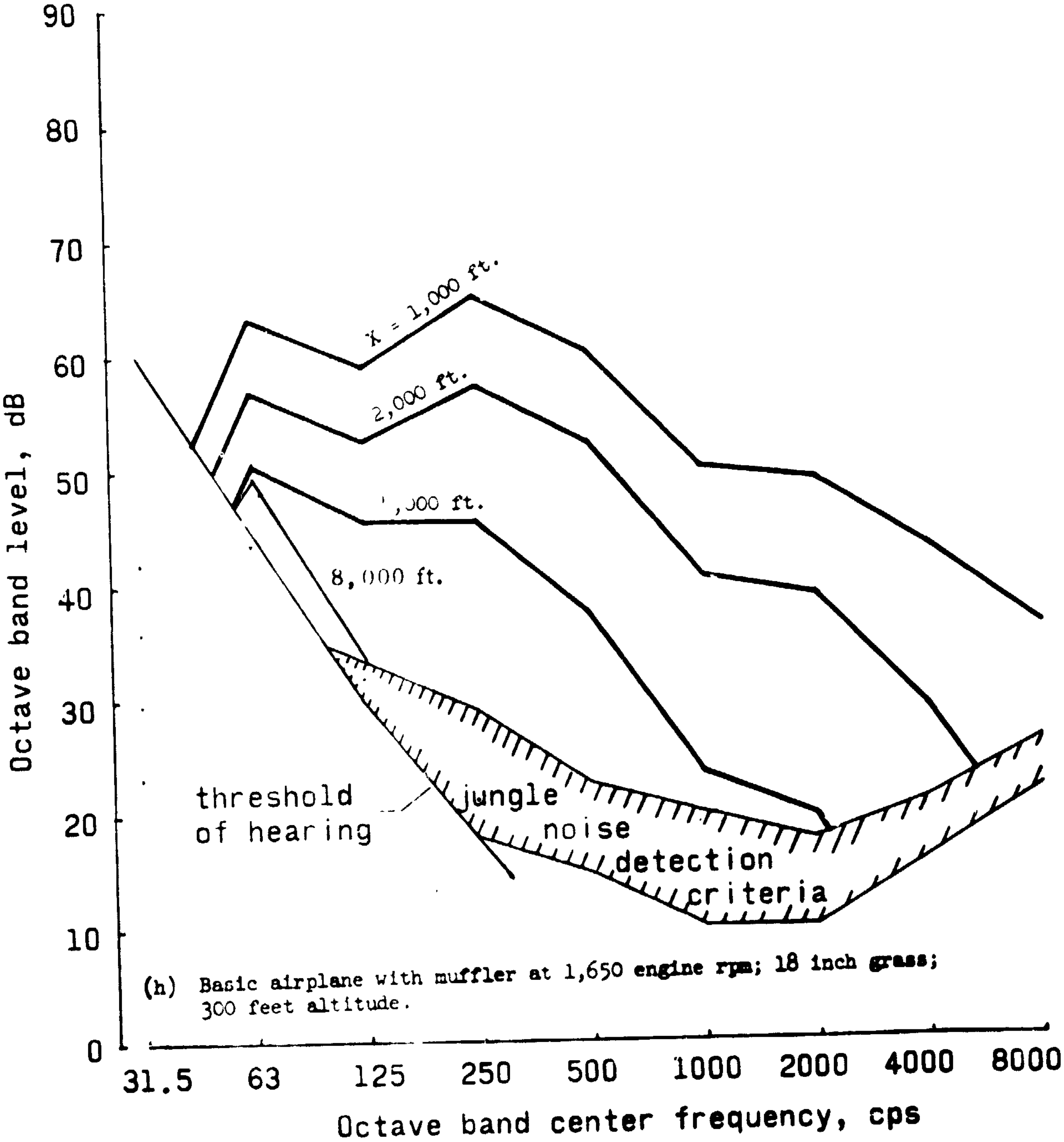


Figure 11.- Continued



(g) Basic airplane at 1,650 engine rpm; 18 inch grass; 300 feet altitude.

Figure 11.- Continued



(h) Basic airplane with muffler at 1,650 engine rpm; 18 inch grass; 300 feet altitude.

Figure 11.- Concluded

APPENDIX A

PROPELLER NOISE AND PERFORMANCE CONSIDERATIONS

By John L. Crigler

For propeller-driven airplanes, the most important parameters to be considered in reducing the propeller noise are the propeller rotational tip speed and the number of blades. Reference A-1 shows that for a given design condition of engine power and airplane speed, the propeller noise can be reduced by a reduction in propeller tip speed, or by an increase in blade number or both. Some reductions may also be realized by decreasing the propeller disk loading (larger, slower turning propellers, operating at the same tip speed).

This appendix contains a description of the procedure used to estimate the performance of several propellers that could be fitted to the design condition of the U-10 airplane, along with estimates of the noise pressures generated by each propeller operating in a low power level-flight cruise at sea level.

Propeller Selections

The unmodified U-10 is a single-engine airplane with a 295-hp Lycoming engine driven by a three-blade 8-ft-diameter constant-speed propeller. The engine-propeller gear reduction ratio is 77:120. The propeller is designed to absorb 280 hp at 3000 engine rpm (1925 propeller rpm) in cruise at 135 knots at sea level.

One alternate propeller design entailed a reduction in propeller diameter to 7 ft, with no change in engine-propeller gearing, in order to reduce the rotational tip speed. Because of the reduced diameter, more blade area was required to absorb the power. Therefore, the number of propeller blades was increased to five to provide an additional reduction in the noise level. For the second propeller modification, in order to further reduce the propeller tip speed, the gear ratio was lowered to 44:120 and the propeller diameter was increased to 9.0 ft. The larger diameter is recommended because of its increased take-off performance. For noise considerations five blades are recommended.

The performance of each of the propellers has been estimated and compared in table A-I. Also listed in table A-I are the number of blades, the solidity required at the 0.7 radius (geometrically similar blades assumed) and the estimated weight of the propellers. The estimated weight is taken from appendix C. The performances listed in the table were estimated with the aid of references A-2, A-3, and A-4.

The propeller noise levels for all configurations were estimated for a distance of 50 ft from the source by the method given in reference A-1 and by the method given in A-5 and are presented in table A-II. For convenience, equation (18) of reference A-5 (neglecting the thrust terms and in a slightly different form) is given as,

$$\rho = \frac{1}{\sqrt{2}} \left[\left\{ \frac{\rho B^3 m^2 \omega^2}{2\pi s} \int_{0.2}^{1.0} J_{mB}\left(mBM_t x\right) A(x) R \, dx \right\}^2 + \left\{ \frac{mBQ}{2\pi R_e^2 s} J_{mB}\left(0.8\, mBM_t\right) \right\}^2 \right]^{\frac{1}{2}} \tag{A-1}$$

The first term in equation (A-1) gives the "thickness noise" or noise due to the blade cross section and is not considered in reference A-1. It may be seen that the second term in equation (A-1) is the same as equation (1) in reference A-1 when the thrust term is neglected. All calculations by both methods are for the 90° aximuth which means that the calculated "thrust noise" becomes zero. The measured noise levels for the 90° azimuth for the basic propeller configuration are also included in the table for comparison. It is seen that the calculated noise levels by both methods are in very close agreement at the fundamental blade passage frequency and that both calculations are in good agreement with the measured data. The discrepancy between measured and calculated data increases with harmonic number but it is seen that the inclusion of the "thickness noise" term greatly improves the agreement.

The noise levels in the table, both calculated and measured, for all the propellers in table A-II are for the same engine power and speed (198 brake horsepower at 2740 engine rpm). The cruise level flight velocity of the U-10 airplane at sea level is approximately 115 knots for 198 hp.

An examination of the data in table A-I and table A-II indicates it is possible to design a somewhat quieter propeller (7.5 dB reduction for the case calculated), with only small losses in performance, by reducing the blade diameter and increasing the blade number, with no change in engine-to-propeller gearing. Markedly larger reductions in noise can be realized for reduced engine-to-propeller gear ratios and increased diameters. Calculations indicate a reduction of about 20 dB at the blade passage frequency below that for the basic propeller for a 9-ft-diameter, five-blade propeller with a gear reduction of 44:120. Only a small loss in static thrust is indicated with no loss in cruise or climb efficiency.

REFERENCES

A-1. Hubbard, Harvey H.: Propeller Noise Charts for Transport Airplanes. NACA TN 2968, 1953.

A-2. Crigler, John L.; and Jaquis, Robert E.: Propeller-Efficiency Charts for Light Airplanes. NACA TN 1338, 1947.

A-3. Crigler, John L.: Comparison of Calculated and Experimental Characteristics for Four, Six, and Eight Blade Single Rotating Propellers. NACA ACR No. 4B04, 1944.

A-4. Biermann, David; and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single and Dual Rotating Tractor Propellers. Report No. 747, NACA, 1942.

A-5. Dodd, K. N.; and Roper, G. M.: A Deuce Programme for Propeller Noise Calculations. Royal Aircraft Establishment Technical Note No. M.S. 45, January 1958.

TABLE A-I

SUMMARY OF PERFORMANCE CALCULATIONS FOR BASIC AND

MODIFIED PROPELLER CONFIGURATIONS

$(280 \text{ hp at } 3000 \text{ rpm}_{engine})$

Configuration	N_p	D	πnD	M_t	B	$\sigma_{0.7R}$	η at 135 knots	η at 86 knots	Static thrust, lb	Weight, lb
Basic	1925	8	806	0.722	3	0.02945 B	0.850	0.740	1300	110
Modification I	1925	7	705	.632	5	.0265 B	.845	.730	1200	95
Modification II	1100	9	518	.464	5	.0274 B	.855	.760	1250	161

TABLE A-II

SUMMARY OF SOUND PRESSURE LEVELS FOR

BASIC AND MODIFIED PROPELLER CONFIGURATIONS

Propeller configuration													
Basic $D = 8$; $B = 3$; $N_p = 1757$; $M_t = 0.66$					Modification I $D = 7$; $B = 5$; $N_p = 1757$; $M_t = 0.577$				Modification II $D = 9$; $B = 5$; $N_p = 1005$; $M_t = 0.425$			
f, cps	mB	dB_{calc} ref. A-1	dB_{calc} ref. A-5	dB meas.	f, cps	mB	dB_{calc} ref. A-1	dB_{calc} ref. A-5	f, cps	mB	dB_{calc} ref. A-1	dB_{calc} ref. A-5
87.8	3	96.5	96.7	95.0	146.5	5	89.0	89.5	83.7	5	77.0	77.0
175.7	6	89.	90.	84.	293.	10	69.5	72.	167.5	10	45.	46.
263.5	9	80.5	82.5	73.5	439.	15	48.5	56.5				
351.5	12	71.	75.	79.	586.	20	27.	42.5				
439.	15	61.5	69.	75.								
527.	18	52.	63.	69								

APPENDIX B

U-10 EXHAUST NOISE REDUCTION

By Tony Lee Parrott

The unmuffled exhaust noise sound pressure level corresponding to an engine speed of 2740 rpm is shown in figure B-1. This spectrum was obtained from a 3-cps-bandwidth analysis of tape recordings of the engine and propeller noise during static tests. The spectrum indicates that the overall noise level from the engine is approximately 109 decibels with the major contribution coming from a 137-cps component corresponding to engine fundamental frequency at the stated rpm of 2740. The dashed line connecting the discrete component levels of the spectrum shown by the symbols will be called the spectrum envelope in order to emphasize the fact that a discrete frequency spectrum is being discussed. It was found to be more convenient to deal with the envelope for the purpose of estimating the effect of various muffler designs on the noise spectrum.

Using the relation for determining the frequency at which the most prominent component of the exhaust noise should be radiated, it was found to be 137 cps which coincided, within the limits of experimental error, with the frequency at which the greater part of the measured exhaust noise was being radiated. All other harmonics were at least 11 decibels below the 137cps peak as indicated in figure B-1.

The procedure for designing a muffler to reduce the exhaust noise on the U-10 aircraft followed the outline presented in the Methods and Procedures section of this appendix. A performance estimate for the near optimum filter arrangement resulting from this procedure is shown in figure B-2. Figure B-2 indicates that an overall noise reduction of 34 decibels is feasible with a 2-cu-ft double expansion chamber-type muffler. This volume magnitude is believed to be practical for the U-10 aircraft since the muffler length would be about 6.66 ft resulting in a fineness ratio that would bring the aerodynamic penality into a tolerable range. Figure B-3 shows the estimated spectrum modification for a 2-cu-ft muffler. Note that the 137-cps component is reduced from 108 decibels to approximately 77 decibels and no other component is greater than 71 decibels. The estimated overall level is found to be 77 decibels.

Figure B-4 shows a schematic diagram of the 2-cu-ft muffler with the various critical dimensions listed. All geometrical dimensions are computed using the assumption that the sound speed in the hot exhaust gas is 2000 ft/sec.

Methods and Procedures

Nature of exhaust noise.- Reciprocating engine exhaust noise is characterized by a discrete frequency spectrum. The frequency spectrum depends upon engine speed, number of cylinders, firing order and exhaust manifold geometry as well as the exhaust-mass-flow-time-history details of the individual cylinders. For an engine whose exhaust manifold geometry is such that the acoustic disturbances from the various cylinders travel the same distance to a common point of expulsion into the atmosphere, then the dominant contribution to the exhaust noise will occur at the so-called engine fundamental frequency which is given by:

$$f_d = \frac{SN}{120}$$

S = engine speed, rpm

N = number of cylinders

In actuality, however, the exhaust manifold geometry may be such that an engine harmonic or subharmonic may contribute the major portion of the total exhaust noise. It is for this reason that measurement and analysis of the exhaust noise for operational conditions must be conducted in order to accurately locate the frequencies at which the major noise components are being radiated. From this knowledge a muffler design and/or modification of the exhaust system can be undertaken to provide some exhaust noise reduction.

Muffling of exhaust noise.- Mufflers for engine-exhaust systems are perhaps more accurately described as low pass acoustic filters designed to have a minimum impedance for steady volume flows and to have a high impedance for oscillating volume flows characteristic of acoustic waves. The high impedance for the sound waves is provided by reactive type acoustic devices and/or by an absorbing medium. The reactive devices consist of expansion chambers or side branch resonators which impede the exhaust noise by reflecting it back into the source. Absorbing media simply convert acoustic energy into heat, hence bringing about attenuation of noise by means of a dissipation process. Reactive devices work well for frequencies up to about 500 to 600 cps, whereas dissipation devices work better for the higher frequencies above 600 cps. Since aircraft engine noise spectra indicate that the greater part of the noise lies in the 20 - 500 cps frequency range, only reactive mufflers will be considered in this report.

Successful aircraft muffler design requires that three criteria be satisfied:

1. Acoustical criterion: Specifies the overall attenuation or noise reduction to be achieved and the detailed modifications of the spectrum by the addition of the muffler.

2. Back pressure criterion: Specifies the minimum pressure drop through the muffler at given operating conditions of temperature and mass flow.

3. Aerodynamic criterion: Specifies the maximum allowable volume and weight as well as restrictions on shape.

Although there is necessarily a trade-off between these three criteria for a given practical application, only the acoustical performance of mufflers will be discussed at present in order to give the reader an appreciation for the upper limits of noise reduction that are possible. The criteria of minimum back pressure and minimum aerodynamic penalty will then be seen to place definite limits on the attainable noise reduction for a given aircraft and operating conditions. Also, it is clearly impractical to reduce engine noise levels more than 9 dB below the levels of other noise sources on the aircraft since the higher level effectively masks the other for differences of this order or greater.

The sound attenuating characteristics of a muffler system are determined by examining the sound pressure spectrum of the exhaust noise that is to be reduced. Then, by essentially a trial and error procedure, various combinations of expansion chamber - resonator combinations are analyzed by means of a general computer program which produces a graph of the attenuation through the muffler as a function of frequency. Usually it is most efficient to begin with the simpliest system and progress to more complicated systems until one is found adequate for the job. A flow chart describing this procedure is shown in figure B-5.

It was not necessary to go through the above entire procedure for each configuration investigated in this report. For example, it was obvious as more experience was gained that a particular type of muffler would be most efficient for a given situation, in which case the design computations were carried out without further ado. Also, it should be pointed out that, whereas many assumptions underlie the computational procedure, the resulting attenuation curves were biased in accordance with experimental results in reference B-1. Hence, it is believed that the resulting estimates of engine noise attenuation are, to some extent, conservative.

REFERENCE

B-1. Davis, Don D., Jr.; Stokes, George M.; Moore, Dewey; and Stevens, George L., Jr.: Theoretical and Experimental Investigation of Mufflers With Comments on Engine-Exhaust Muffler Design. NACA TN-1192, 1954.

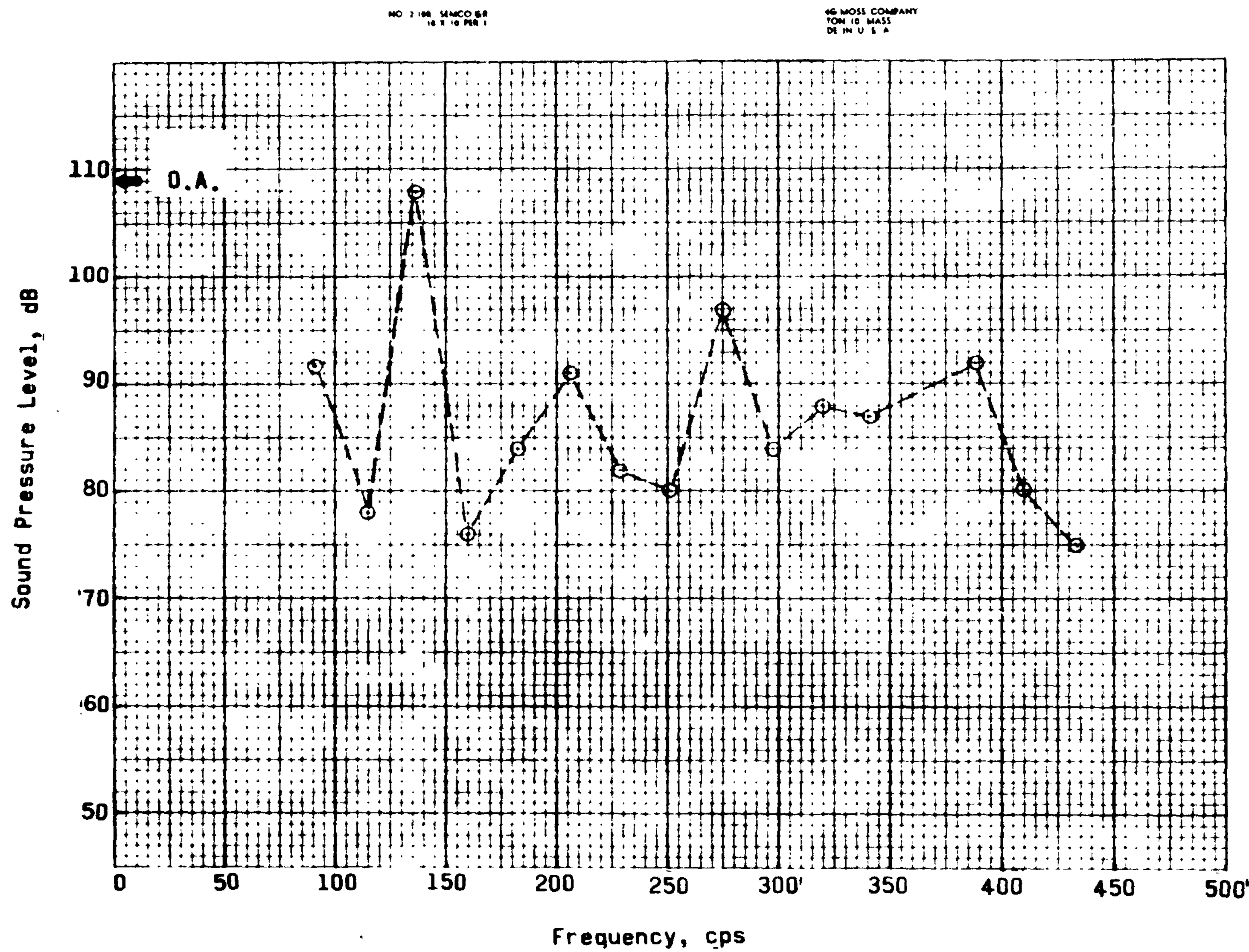


Figure B-1.- U-10 exhaust noise spectrum envelope at distance of 50 feet from aircraft.

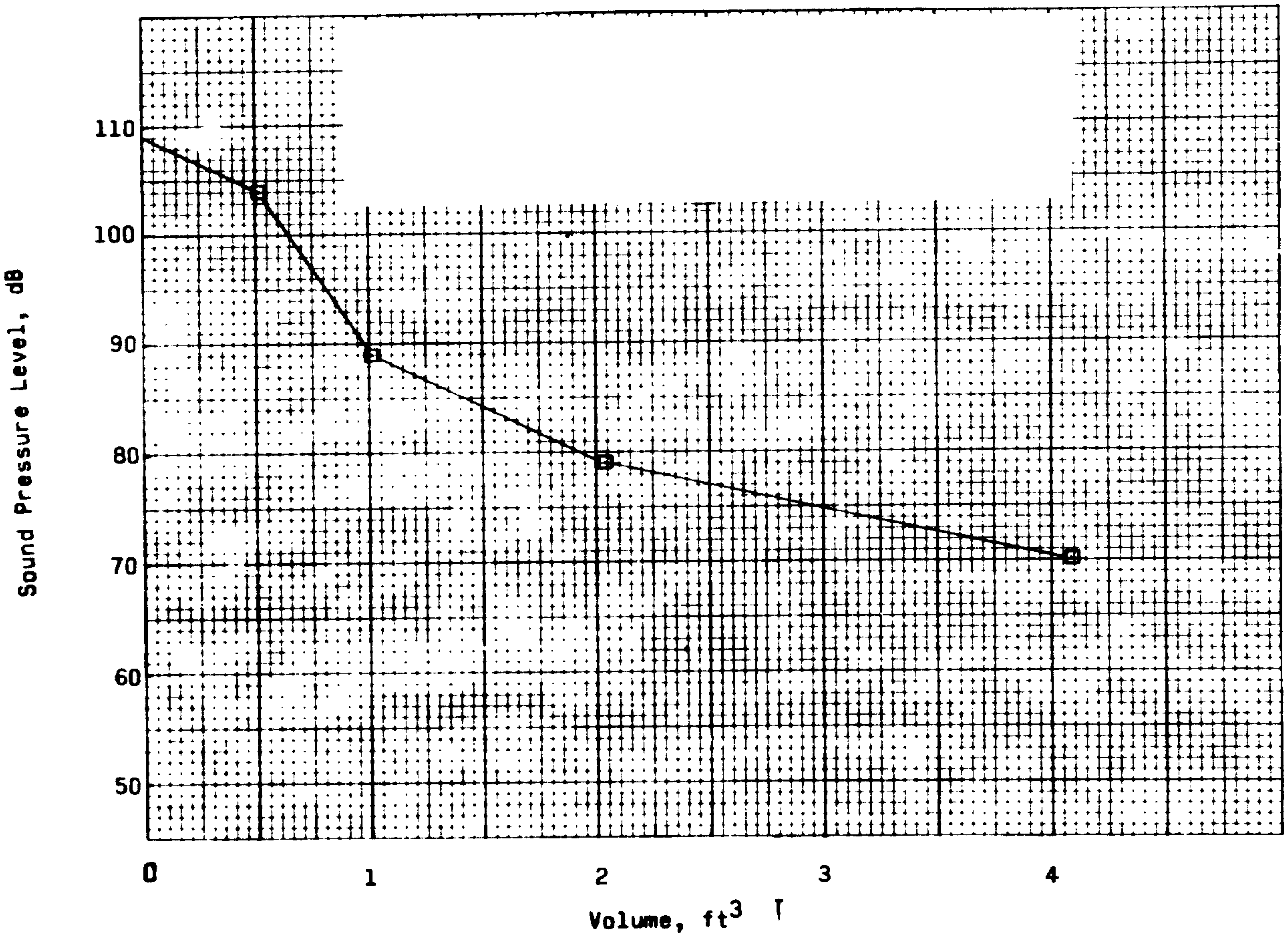


Figure B-2.- Muffler performance as a function of volume based on estimated overall insertion loss at 50 feet from aircraft using double expansion type filters.

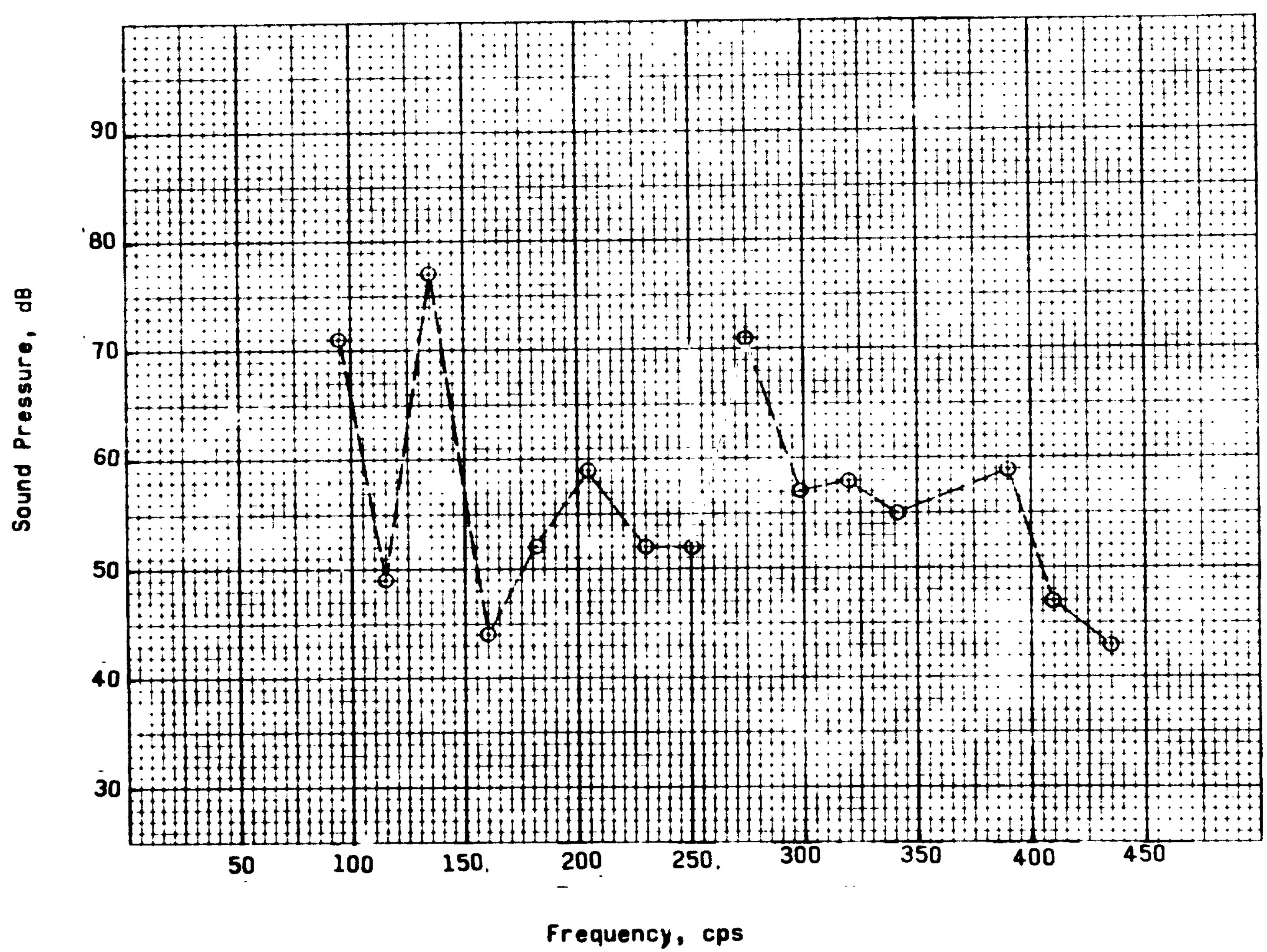
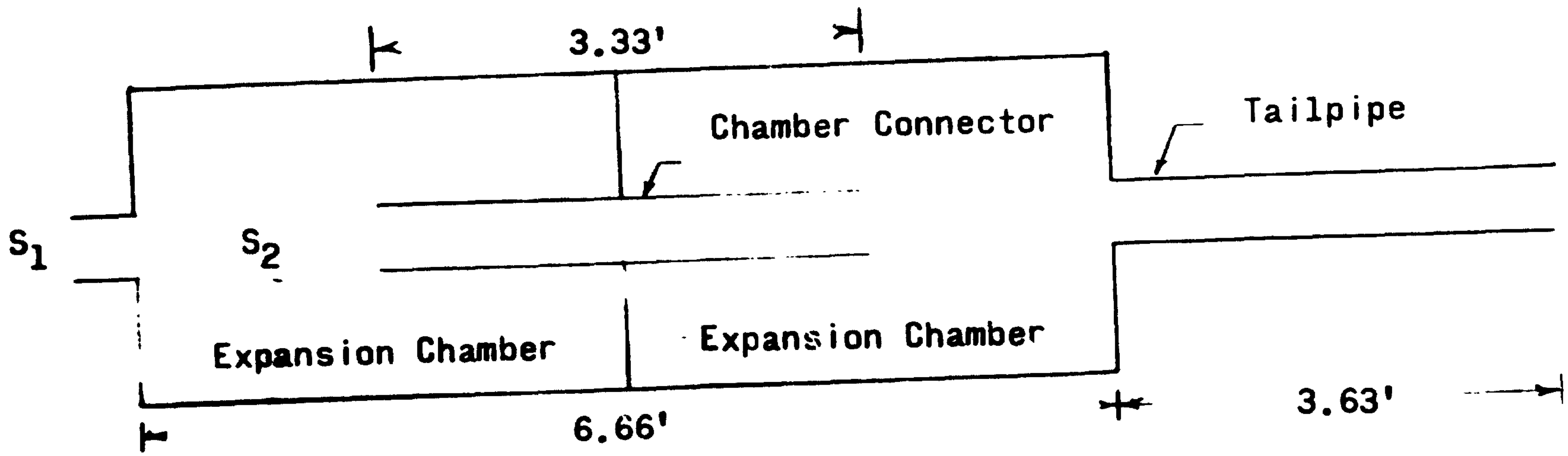


Figure B-3.- Estimated spectral performance of a two cubic foot muffler using double expansion type filter elements.



$S_1 = .0383\ ft^2$
$M = S_2/S_1 = 8$
$S_2 = .3064\ ft^2$
$Volume = 2.06\ ft^3$

Figure B-4.- Schematic diagram of muffler with double expansion chamber type filter elements.

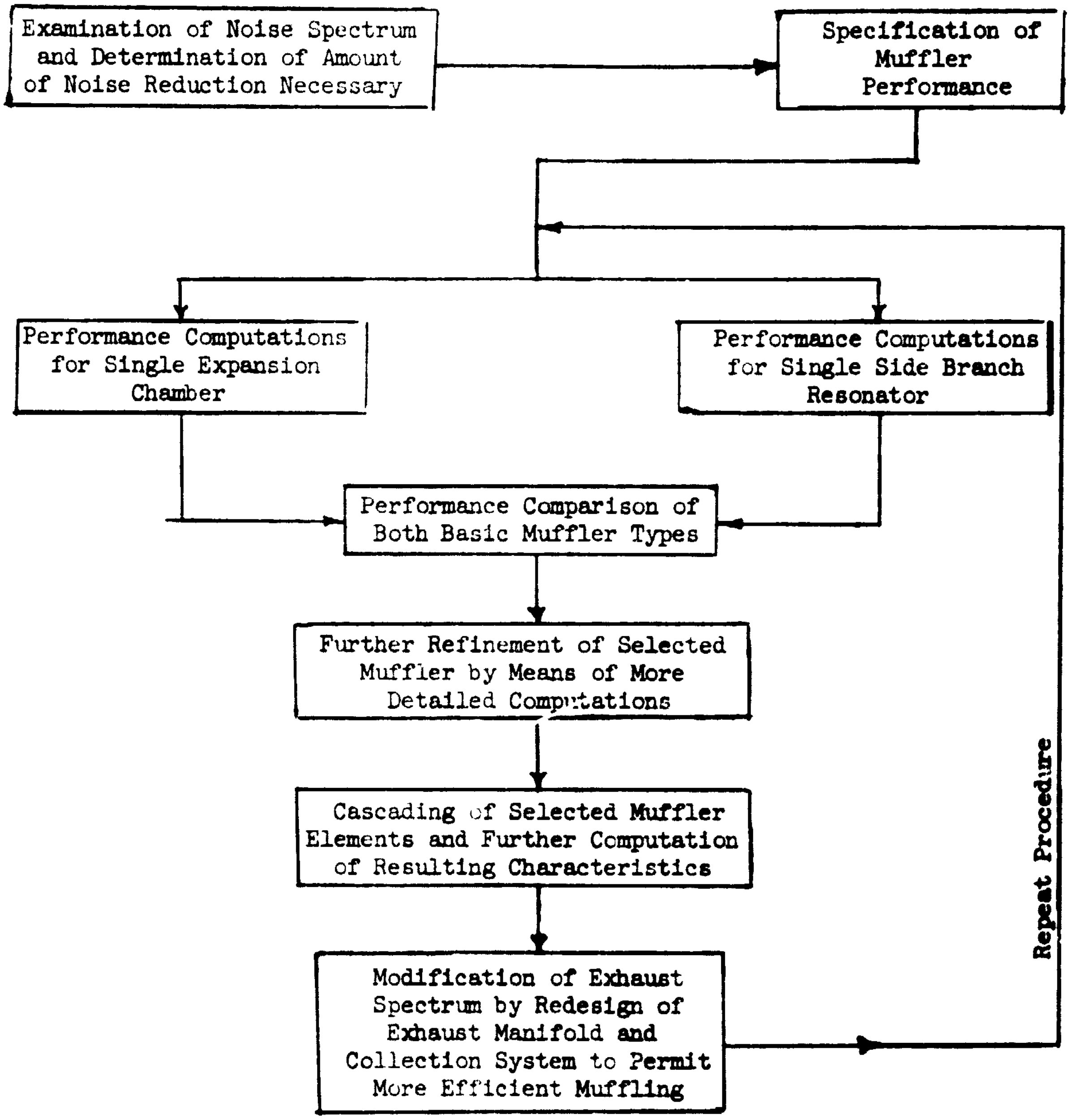


Figure B-5.- Flow diagram illustrating muffler computation procedure employed for this study.

APPENDIX C

WEIGHT ESTIMATES

By M. L. Sisson

Propeller and Reduction Gear Weight Estimation

Propeller blade weights are based on scaling factors applied to the existing aluminum alloy blade. This method assumes that the thickness-to-chord ratio at each percentage of propeller tip radius station is maintained. The weight of each aluminum alloy blade becomes:

$$\text{weight}_1 = \left(\frac{\text{chord}_1}{\text{chord}_0}\right)^2 \times \frac{\text{diameter}_1}{\text{diameter}_0} \times \text{weight}_0,$$

where subscript "0" refers to the original blade and subscript "1" refers to the new blade.

Propeller hub weights were scaled from the existing controllable-pitch hub. The scaling factor used was the total blade centrifugal force (centrifugal force per blade times the number of blades) raised to the eight-tenths power.

Weights of production reduction gears of three reciprocating engines were obtained by subtracting the weights of direct-drive engines from the weights of the same engines with reduction gearing. These three weights were then plotted versus normal rating output torque on log-log graph paper (fig. C-1). It was found that a straight line very accurately fitted these cases. Weights for modified reduction gears were read from this curve.

Weights of the propeller modifications are shown in table C-I.

Exhaust System Weight Estimation

The exhaust muffler configurations investigated were double-cavity type, 6.66 feet long between end heads. A tube half the length of the muffler was centered in a bulkhead located at the midlength of the muffler. A tail pipe of 2-3/4 inches outside diameter and 3.63 feet in length is included. Weights were computed on the basis of using 20 gage (0.037 inch) stainless steel. An allowance of 3.5 pounds was added for a short length of exhaust pipe, brackets, and clamps. The increased weights of the system were plotted versus muffler volume producing the curve of figure C-2.

TABLE C-I

Propeller and Gear Weight Summary

Basic

Weight of three blades	51.0 lb
Hub weight	59.0
Total propeller weight	110.0 lb
Reduction gear weight, $\frac{77}{120}$ ratio	30.0 lb

Modification I

Five-blade, 7-foot diameter, $\frac{b}{R}$ = 90% of standard, gear ratio $\frac{77}{120}$

Weight of five blades	46.1 lb
Hub weight	48.9
Total propeller weight	95.0 lb
Less standard propeller weight	-110.0
Weight increase	-15.0 lb

Modification II

Five-blade, 9-foot diameter, $\frac{b}{R}$ = 96% of standard, gear ratio $\frac{44}{120}$

Weight of five blades	111.5 lb
Hub weight	49.5
Total propeller weight	161.0 lb
Less standard propeller weight	-110.0
Propeller weight increase	51.0 lb
Reduction gear weight increase	17.0
Total weight increase	68.0 lb

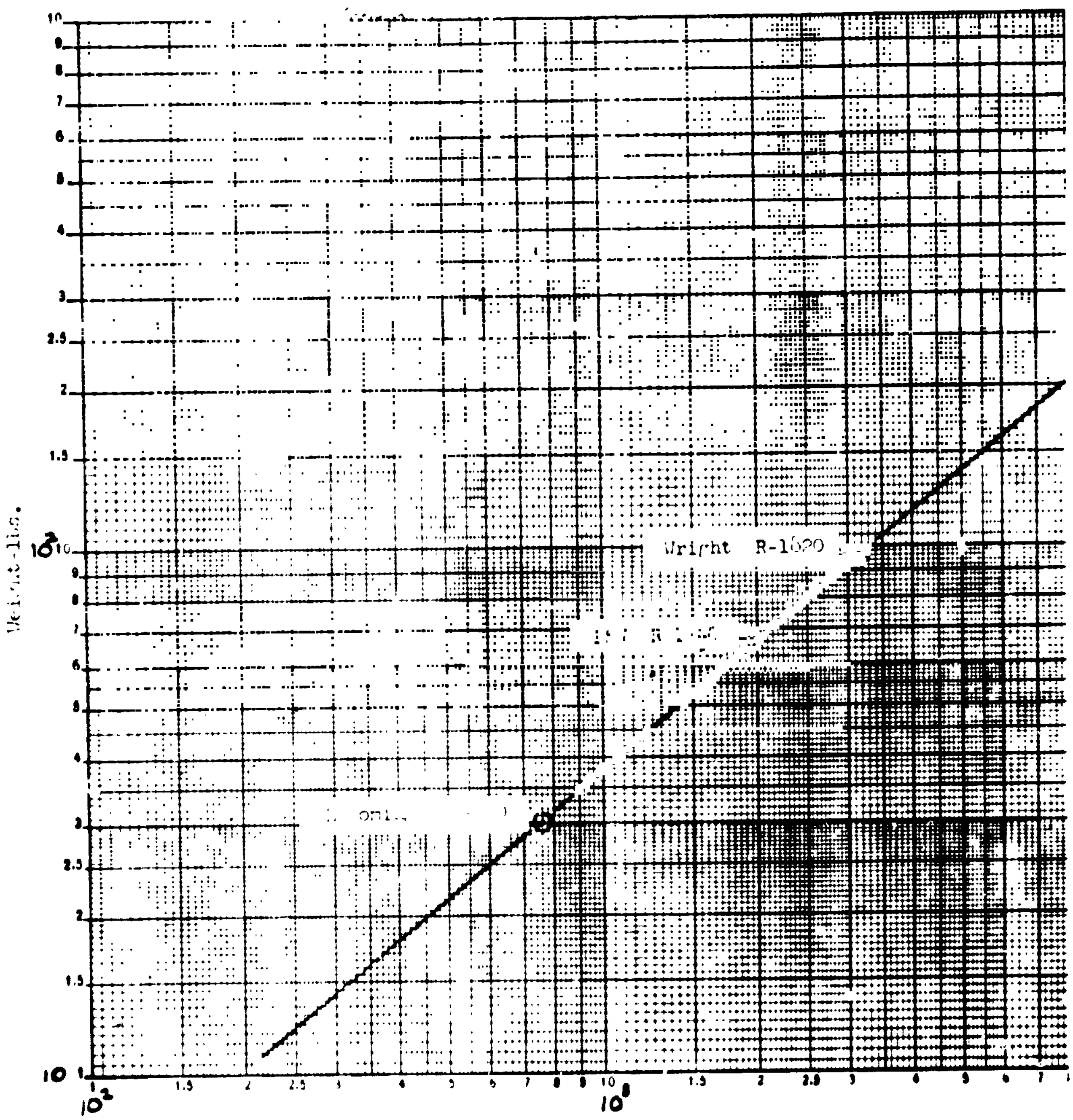


Figure - .7 ...proxima... ...ine Reduction Gear Weight

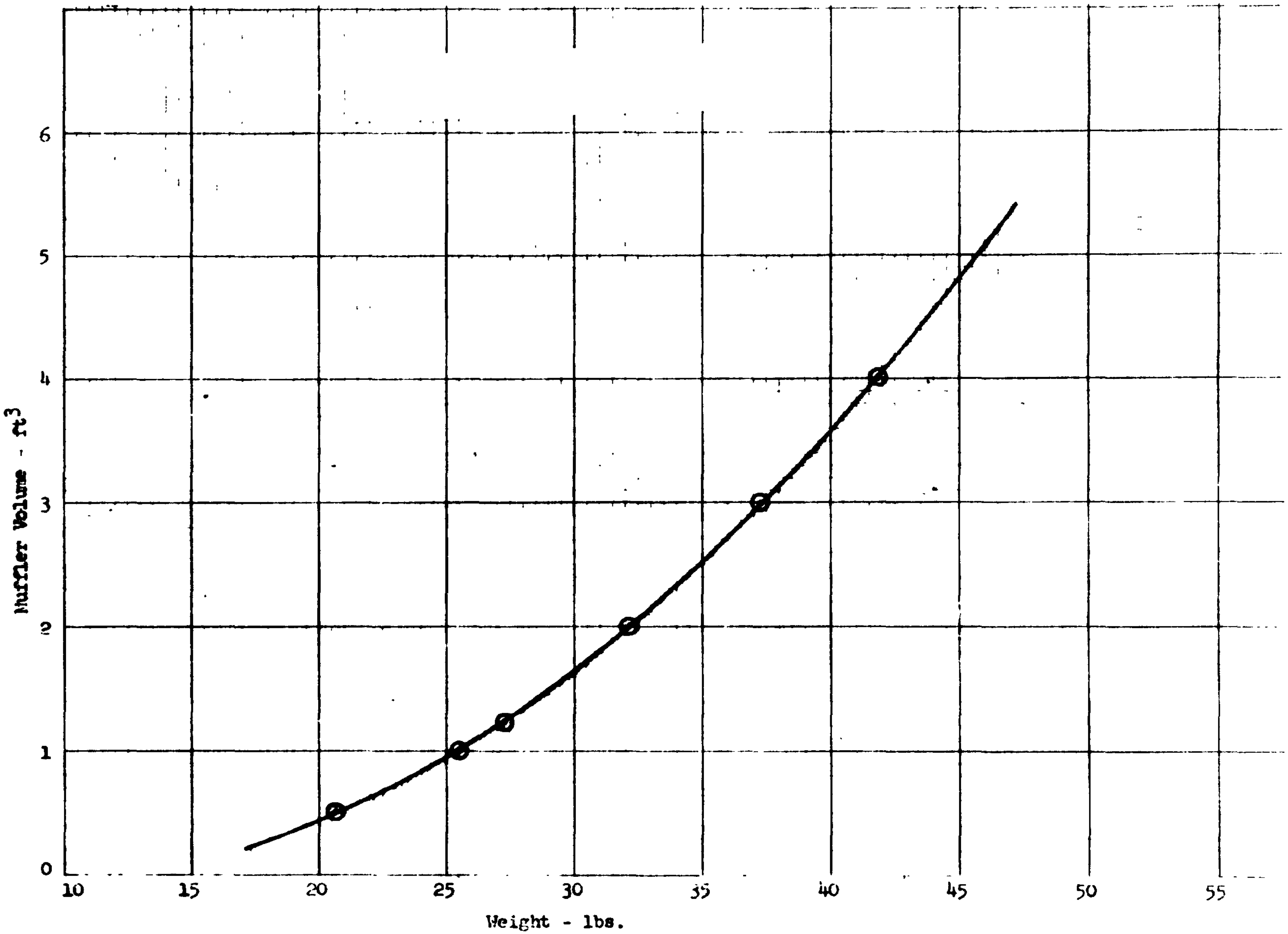


Figure C-2. — Estimated weight of muffler system for U-10 aircraft.

APPENDIX D

Performance, Stability and Control

By Ernie L. Anglin and James L. Hassell, Jr.

Method of estimating performance.- Flight test results reported in references D-1 and D-2 for the basic U-10B (formally designated L-28) aircraft were used to obtain the brake horsepower required for level flight through the speed range for the take-off and cruise configurations. The propeller characteristics of the 3-blade, 8-foot diameter, constant-speed Hartzell HC-93220-181-10151C-5 propeller were obtained from the manufacturer; these characteristics were derived from experimental results of reference D-3 for a 3-blade propeller having an activity factor of 90. Thrust horsepower required for level flight as a function of true airspeed was then determined from the relation:

$$THP = \eta \, BHP$$

Basic lift-drag polars were computed using the aircraft gross weight and thrust horsepower required for level flight for both take-off and cruise configurations. It should be noted that these lift-drag polars include the effects of the automatic leading-edge slats and the propeller slipstream. For the purposes of this study, it is believed that these polars provide a valid basis for calculating the differences in performance attributable to the various propeller and muffler modifications considered. None of the muffler configurations considered had frontal areas large enough to affect the basic lift-drag polars significantly, and therefore the same basic polars were used in the performance calculations of the modified configurations. The thrust horsepower required for the modified configurations was different from that of the basic U-10B only because of the increased weights of each modification which are given in Table D-I.

Thrust horsepower available is a function of the engine brake horsepower, the power absorbing capability of the various propellers and the corresponding propeller efficiencies. The U-10B is equipped with a Lycoming GO-480-GID6 engine having sea level normal rated power of 280 BHP at 3000 rpm and take-off rated power of 295 BHP at 3400 rpm. Five percent power losses were assumed in all calculations to account for accessory power extraction and non-optimum engine operating conditions. The propeller efficiencies and thrust coefficients of the various modified propellers were established using experimental data of reference D-4 and the theoretical method of reference D-5.

Flight performance was then calculated by the classical methods utilizing the established power required - power available data for the basic U-10B and each modification. The take-off performance in each case is based on the engine developing take-off rated power, lift-drag data for the configuration with trailing-edge flaps deflected 20 degrees and with the aircraft operating from a firm sod runway.

Method of estimating stability and control.- The flight test results of reference D-6 were used for establishing the stick-fixed and stick-free neutral points for the basic U-10B airplane. (The Helio model 391 of reference D-6 differs from the U-10B only slightly in external configuration in that it is equipped with a smaller engine and has somewhat shorter nose cowl.) Inasmuch as none of the modifications was deemed of sufficient magnitude to affect the aerodynamic neutral points, any changes in static stability would simply be related to the changes in center-of-gravity positions given in Table D-I. Control characteristics could be affected by changes in slipstream dynamic pressure due to the various propeller modifications and by the secondary effects of increased static stability. Both of these factors were investigated briefly.

Results of performance calculations.- Performance calculations were made for the basic U-10B airplane and for two modifications involving different propellers, reduction gears and mufflers. The weight and balance summary given in Table D-I and plotted in figure D-1 indicate that modification II results in a forward shift of the center of gravity outside of the FAA certificated limits. In view of the fact that numerous flight tests have been conducted outside of these certificated limits as reported in references D-1 and D-2 (see data points on figure D-1) it is felt that the modest change in center-of-gravity location for modification II should be acceptable but that this analysis does not preclude the necessity for the manufacturer to prove the structural integrity of the aircraft should any of the modifications be adopted.

The lift-drag polars for the basic U-10B airplane as derived from the flight test results of reference D-1 are presented in figure D-2. These polars were used in the performance calculations for all configurations inasmuch as the aerodynamic cleanness of the modified configurations were not significantly affected by the small diameter mufflers located under the belly of the aircraft. The propeller characteristics of the basic and modified propellers are presented in figure D-3. These results together with the engine brake horsepower available and the corresponding gross weights given in Table D-I were used to calculate the thrust horsepower available for each case and these data are presented as a function of true airspeed in figure D-4. The thrust horsepower required for level flight for each case is also presented in figure D-4. These power available - power required relationships are then the basis for the normal-rated-power performance calculations summarized in table D-II. The variation of propeller thrust with speed for each case was calculated from thrust coefficients based on take-off rated power and the results are presented in figure D-5. These data were the basis for the take-off performance calculations.

As indicated by the results of the study which are tabulated in Table D-II, the performance penalties attributable to the two modifications are relatively modest: the total take-off distance to clear a 50-foot obstacle is increased by about 6 percent, the maximum rate-of-climb capability is reduced by 2 to 5 percent, but maximum speed and stall speed are essentially unaffected. It should be noted that despite the fact the "quick-fix" modification (Mod. I) had the lowest static thrust (fig. D-5), its take-off performance was almost equal to that of the more sophisticated modification II; this may be attributed to the relatively insignificant weight penalty for modification I as compared with modification II (see Table D-I).

Results of stability and control estimate.- The U-10B airplane is basically a five-place utility light plane, and as such it was designed for a rather wide permissable center-of-gravity range (refer to fig. D-1). Actual flight tests have been conducted well beyond the FAA certificated limits as illustrated by the results of reference D-1, which covered a center-of-gravity range from approximately 31 to 43 percent MAC at a gross weight of approximately 3900 pounds. In view of these results, the center-of-gravity locations ranging from 29.7 to 33.2 percent MAC for the modifications proposed in this study appear to be satisfactory. Quantitative measurements of the stick-fixed and stick-free neutral points are reported in reference D-6 for the Helio Model 391 aircraft which is basically similar aerodynamically to the Helio U-10B, and these flight test results are reproduced as Part 1 of Table D-III. With these results as a basis, the minimum static margins for the cases of the present study are presented as Part 2 of Table D-III. These static margins are adequate for all cases. It is of interest to note, however, that stick-fixed stability is most critical for the take-off configuration (flaps deflected 20°) whereas stick-free stability is most critical for the landing configuration (flaps deflected 40°).

Control power during take-off could be affected considerably by the variation of propeller diameters as proposed in this study, inasmuch as slipstream dynamic pressure is directly a function of propeller diameter. The total dynamic pressure at the tail was calculated from the expression:

$$q_t = q_o + \frac{4T}{\pi D^2}$$

where:

q_o = free stream dynamic pressure

$$\frac{4T}{\pi D^2} = \frac{T}{A} = \frac{\text{thrust}}{\text{propeller disc area}}$$

The results of this calculation for the basic U-10B and each modification are presented in figure D-6 for the take-off power condition as a function of airspeed. These calculations indicate that the 7-foot diameter propeller (Mod. I) would produce increases in dynamic pressure at the tail of the order of about 20 percent whereas the 9-foot diameter propeller (Mod. II) would result in decreases of the order of 25 percent. What this means in terms of aircraft handling qualities is that the response to elevator and rudder control at a given speed during take-off would be more sensitive in the case of the 7-foot diameter propeller and less sensitive in the case of the 9-foot diameter propeller, and the change in sensitivity would be directly proportional to the change in dynamic pressure at the tail. Similar results would apply to the power approach condition where control characteristics at very low flight speeds are of primary concern. These propeller slipstream effects have no bearing on the tail contributions to either longitudinal or lateral directional stability, of course.

REFERENCES

D-1. Swanson, Harold J., Jr.; and Baldwin, Robert L.: U-10B Limited Category II Performance in Landplane and Floatplane Configurations. AFFTC-TDR-64-5, April 1964.

D-2. Calderon, Juan M.; Dobyns, Russell M.; and Campbell, John K.: L-28A Air Force Flight Evaluation. AFFTC-TDR-59-38, January 1960.

D-3. Gray, W. H.: Wind-Tunnel Tests of Single- and Dual-Rotating Tractor Propellers at Low Blade Angles and of Two- and Three-Blade Tractor Propellers at Blade Angles Up to 65°. NACA WR L-316, February 1943.

D-4. Biermann, David; and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single- and Dual-Rotating Tractor Propellers. NACA TR 747, 1942.

D-5. Crigler, John L.: Comparison of Calculated and Experimental Propeller Characteristics of Four-, Six- and Eight-Blade Single-Rotating Propellers. NACA WR L-362.

D-6. Craig, A. J.: Evaluation of the Performance, Stability and Control of the Helio Courier Airplane. University of Wichita, Contract DA-44-177-TC-369, February 1957.

D-7. Anon: Weight and Balance Report Helio Model H-395 and H-395A, Serial No. 584, Reg. No. 63-8091. February 11, 1963.

D-8. Anon: Federal Aviation Agency Aircraft Specification No. 1A8, June 3, 1965.

TABLE D-I. - WEIGHT AND BALANCE SUMMARY

Case	Weight Empty, lbs	Gross Weight, lbs	Gross Weight C.G., % MAC
Basic U10B	2309	3000	32.2
Mod. I	2321	3017	33.2
Mod. II	2409	3100	29.8

Note: Useful load (same for all cases):

Pilot	200 lbs
Fuel	472 lbs
Oil	19 lbs
Total	691 lbs

Source of Weight and Balance Changes

	Propeller and Hub				Reduction Gear			Muffler and Hardware		
Case	D, ft	B	Wt, lbs	Arm, in	Ratio	ΔWt, lbs	Arm, in	Size, ft^3	Wt, lbs	Arm, in
Basic	8	3	110	8.75	77/120	--	--	--	--	--
Mod. I	7	5	95	8.75	77/120	--	--	2.00	32	127
Mod. II	9	5	161	8.75	44/120	17	14.25	2.00	32	127

TABLE D-II. - PERFORMANCE SUMMARY

Item		Basic U-10B	Modification I	Modification II
Gross weight, lbs		3,000	3,017	3,100
Propeller diameter, ft		8	7	9
Propeller blades		3	5	5
Gear reduction		.6415	.6415	.3667
Muffler volume, ft^3		——	1.25	2
Take-off distance at SL with T.O. rated power				
Ground run, ft		236	252	245
Air distance to clear 50-ft. obstacle, ft		284	301	304
Total T.O. distance, ft		520	553	549
Percent difference from basic U-10B		--	+6.3	+5.6
Maximum rate of climb with NRP, ft/min	SL	1,460	1,408	1,431
	5,000	1,120	1,079	1,098
	10,000	815	781	789
	15,000	514	485	497
	20,000	159	143	143
NRP Service Ceiling, ft		21,100	20,700	20,700
Velocity for best rate of climb with NRP, knots, TAS	SL	80	85	81
	5,000	85	86	86
	10,000	86	87	88
	15,000	93	93	95
	20,000	101	101	103
V_{max} with NRP, knots, TAS	SL	143	143	144
	5,000	141	141	142
	10,000	139	139	139
	15,000	134	134	134
	20,000	123	122	123
Cruise configuration V_{stall}, knots, TAS	SL	40	40	40
	5,000	43	43	44
	10,000	46	46	47
	15,000	50	50	51
	20,000	55	55	55

Note: Five percent power losses were assumed in all calculations to account for accessory power extraction and non-optimum operating conditions.

TABLE D-III. - LONGITUDINAL STABILITY.

Part 1 - Helio Model 391 Neutral Point Data (from flight tests reported in reference D-6):

C_L	V, knots for GW = 3000 lbs	N_o, stick-fixed neutral point			N_f, stick-free neutral point		
		Cruise	Take-Off	Landing	Cruise	Take-Off	Landing
.4	98.0	50.8			51.8		
.6	80.0	46.0	40.4		50.7		
.8	69.0	46.0	40.4		50.7		42.8
1.0	62.0	46.0	40.2	55.4	50.7		42.7
1.2	56.5	46.0	39.8	55.1			42.6
1.4	52.5		39.5	54.6		57.7	42.5
1.6	49.0		39.2	54.1		54.0	42.4
2.0	44.0		38.3	52.8		47.4	41.8
2.4	40.0			51.8			41.8

Part 2 - Minimum Static Margins for Cases of Present Study:

Case	Center-of-Gravity Position, % MAC	Minimum Static Margins		
		Cruise	Take-Off	Landing
Basic U-10B	32.2	13.8	6.1	19.6
Mod. I	33.2	12.8	5.1	19.6
Mod. II	29.8	16.2	8.5	22.0

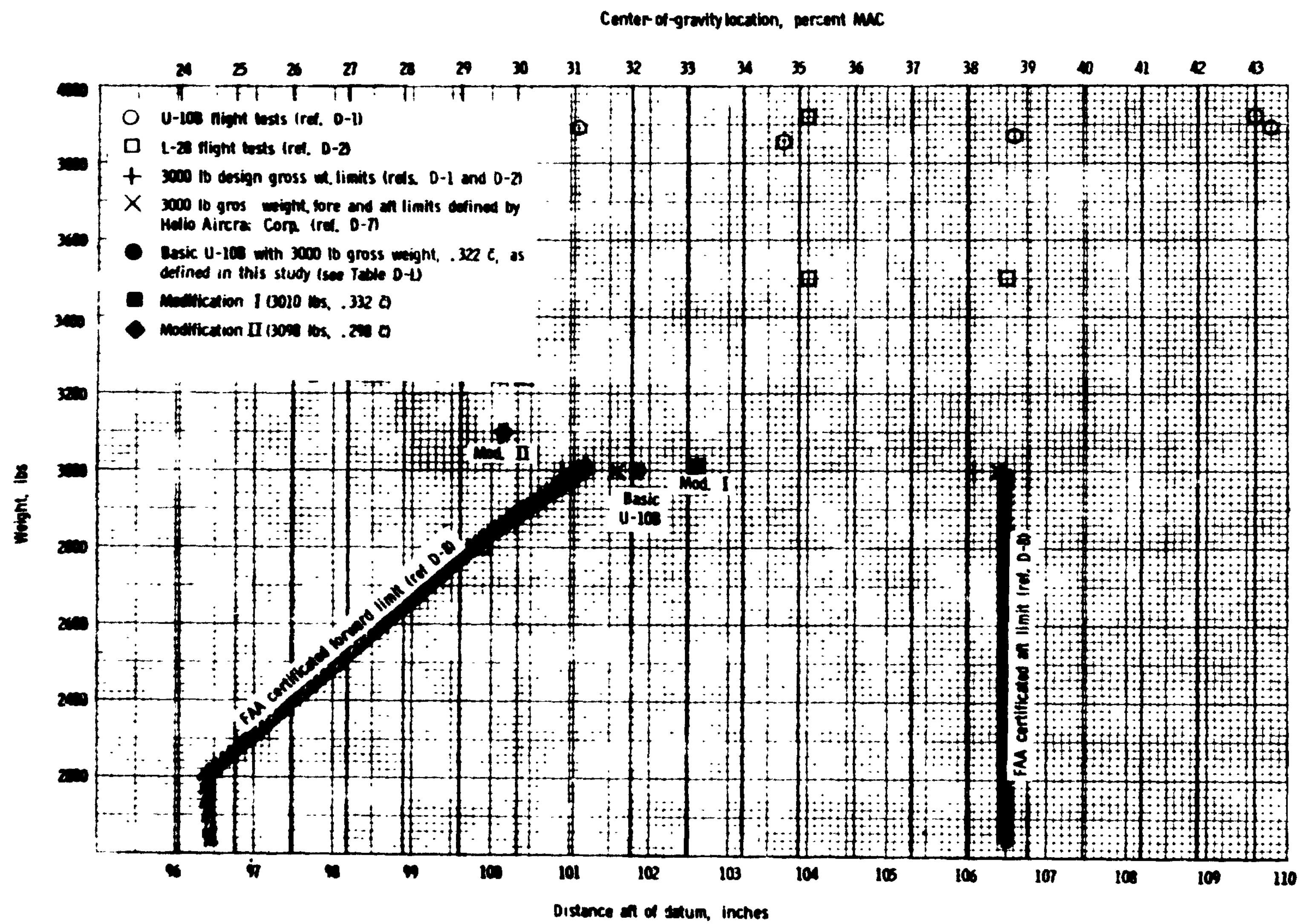


Figure D-1. - Weight and center-of-gravity of the basic U-10B airplane and the modified configurations as related to FAA certificated limits and to actual flight tests conducted outside of the certificated limits.

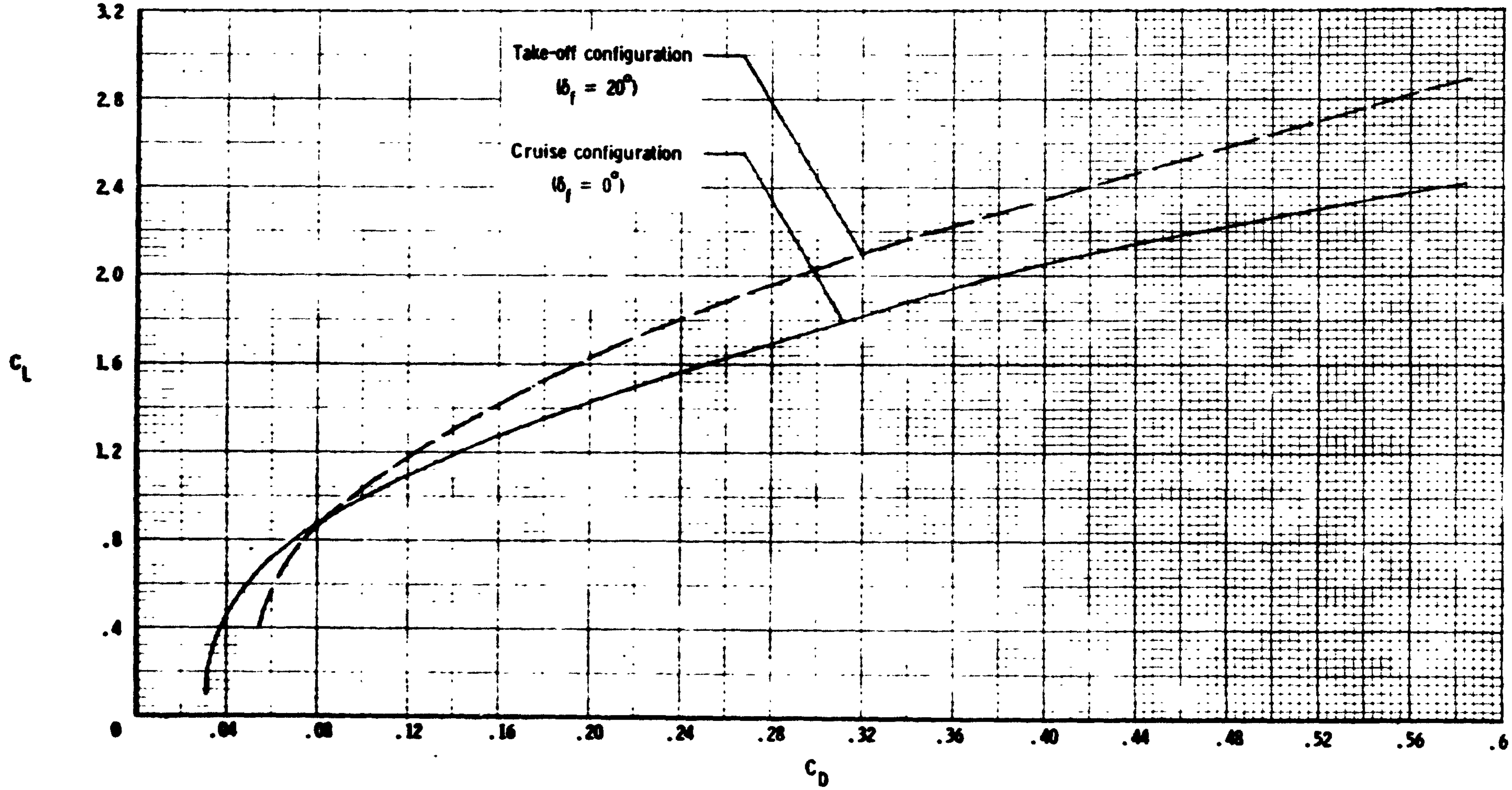


Figure D-2. - Lift-drag polars for the U-10B airplane as derived from flight test results of reference D-1. (Effects of automatic leading-edge slats and propeller slipstream are included in the data presented.)

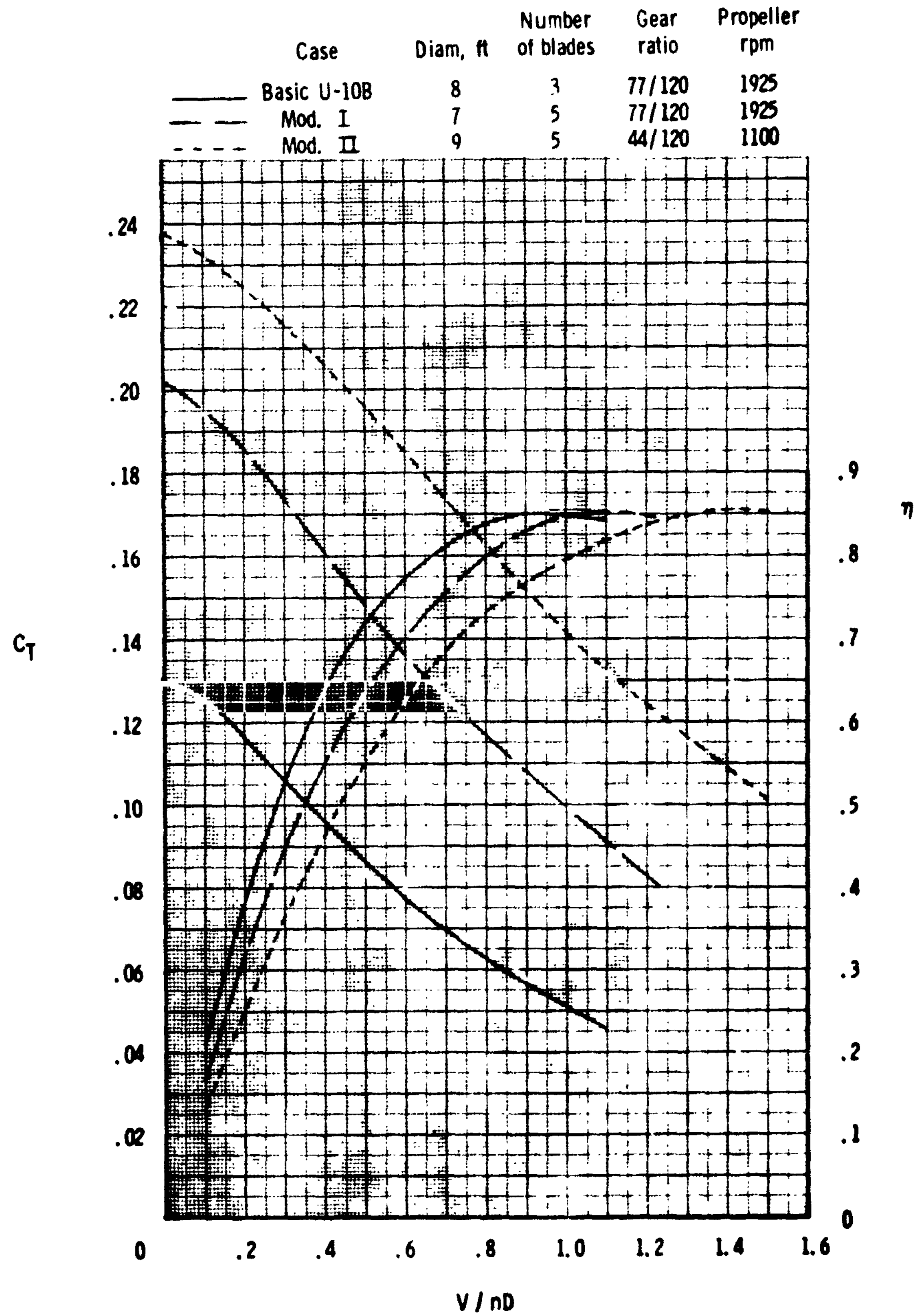


Figure D-3. - Comparison of propeller efficiency and thrust coefficient characteristics of the basic (Hartzell HC-93220-181-10151C-5) propeller and the two proposed propellers.

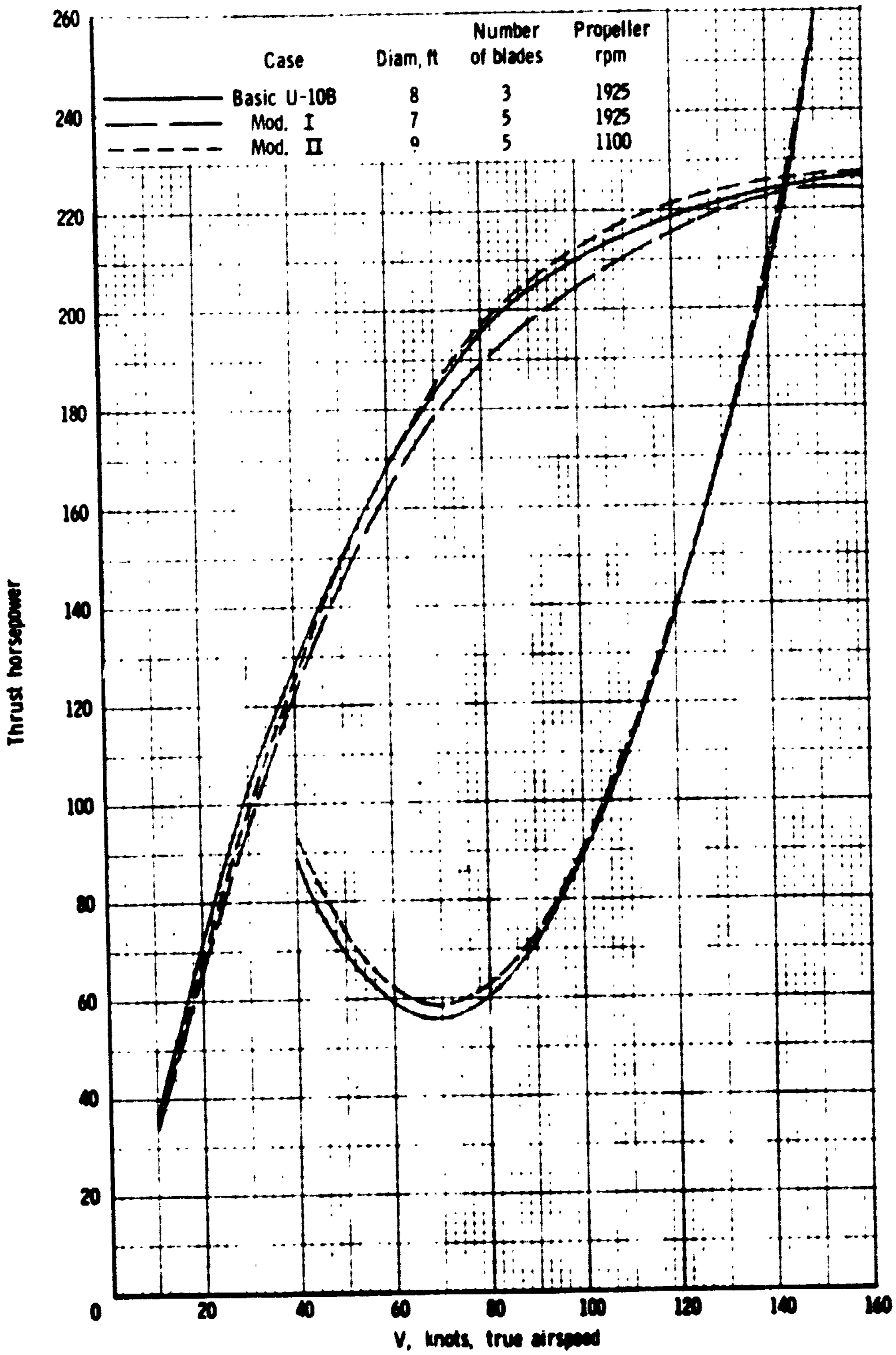


Figure D-4. - Comparison of power available and power required for the basic U-10B airplane and the modified configurations at sea level standard conditions with normal rated power. (Five percent power losses assumed to account for accessary power extraction and non-optimum operating conditions in all cases.)

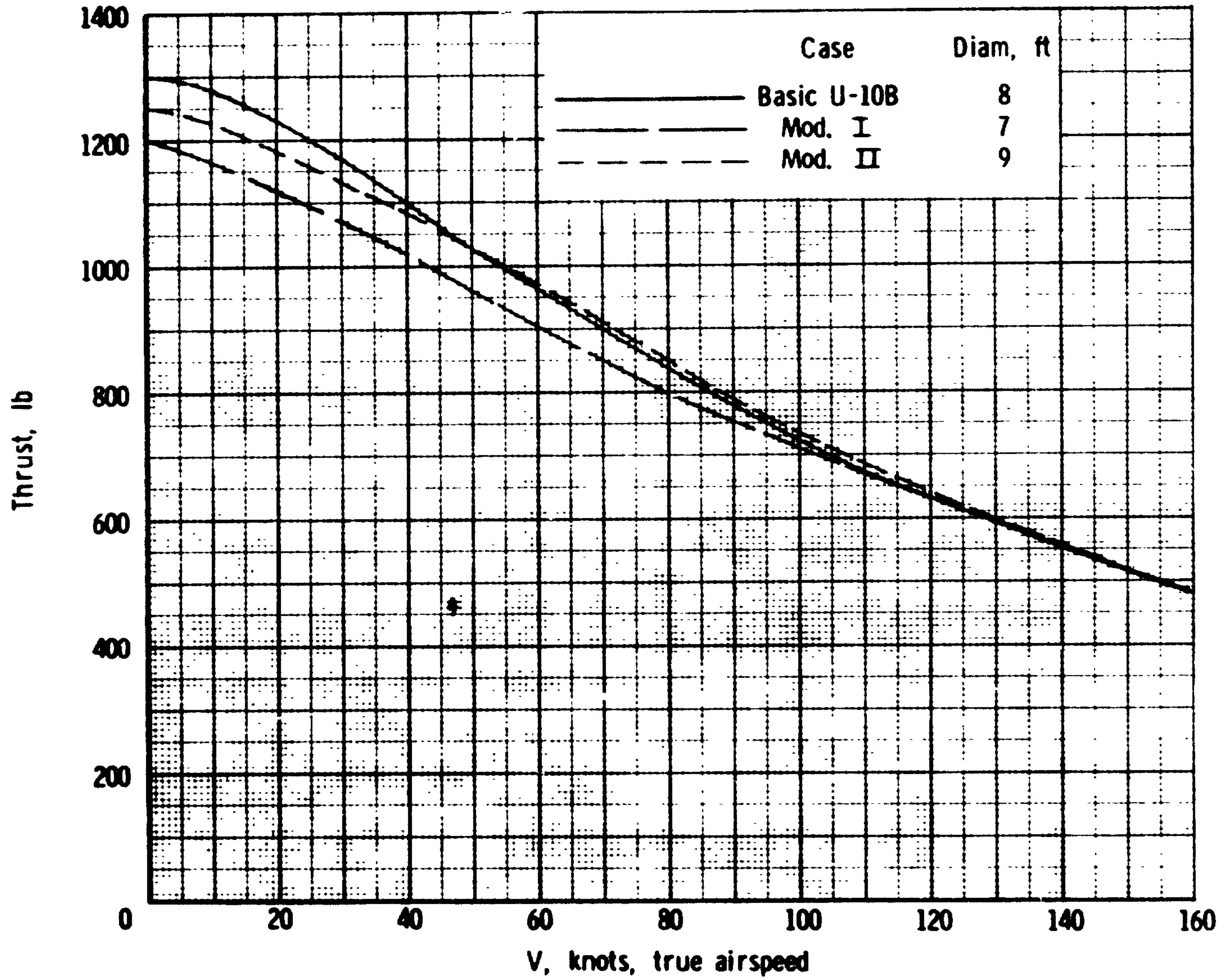


Figure D-5. - Comparison of the variation of thrust with airspeed for the basic U-10B airplane and modified configurations with take-off rated power at sea level standard conditions. (Five percent power losses assumed to account for accessory power extraction and non-optimum operating conditions.)

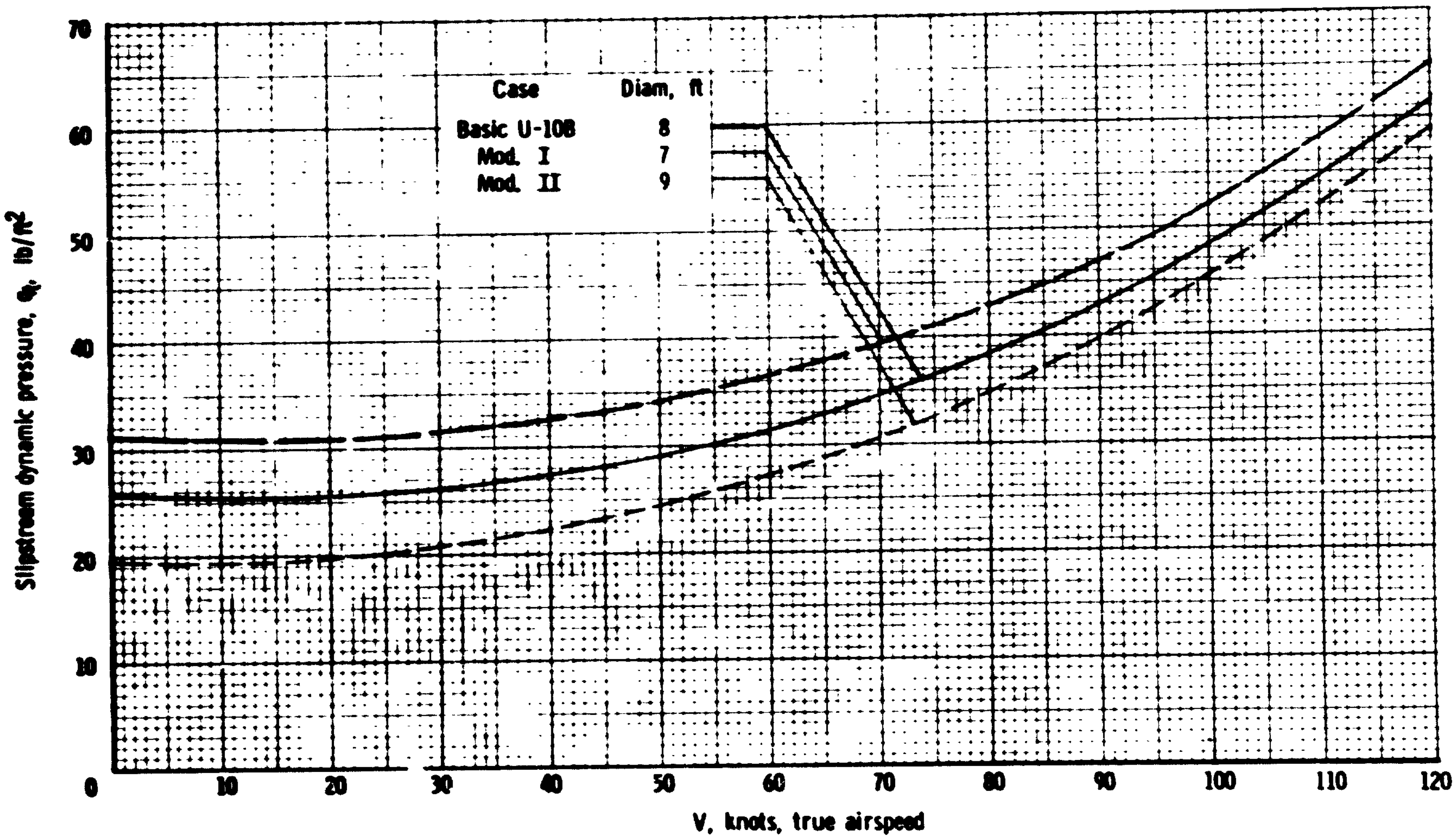


Figure D-6. - Calculated variation of slipstream dynamic pressure with airspeed for take-off rated power.